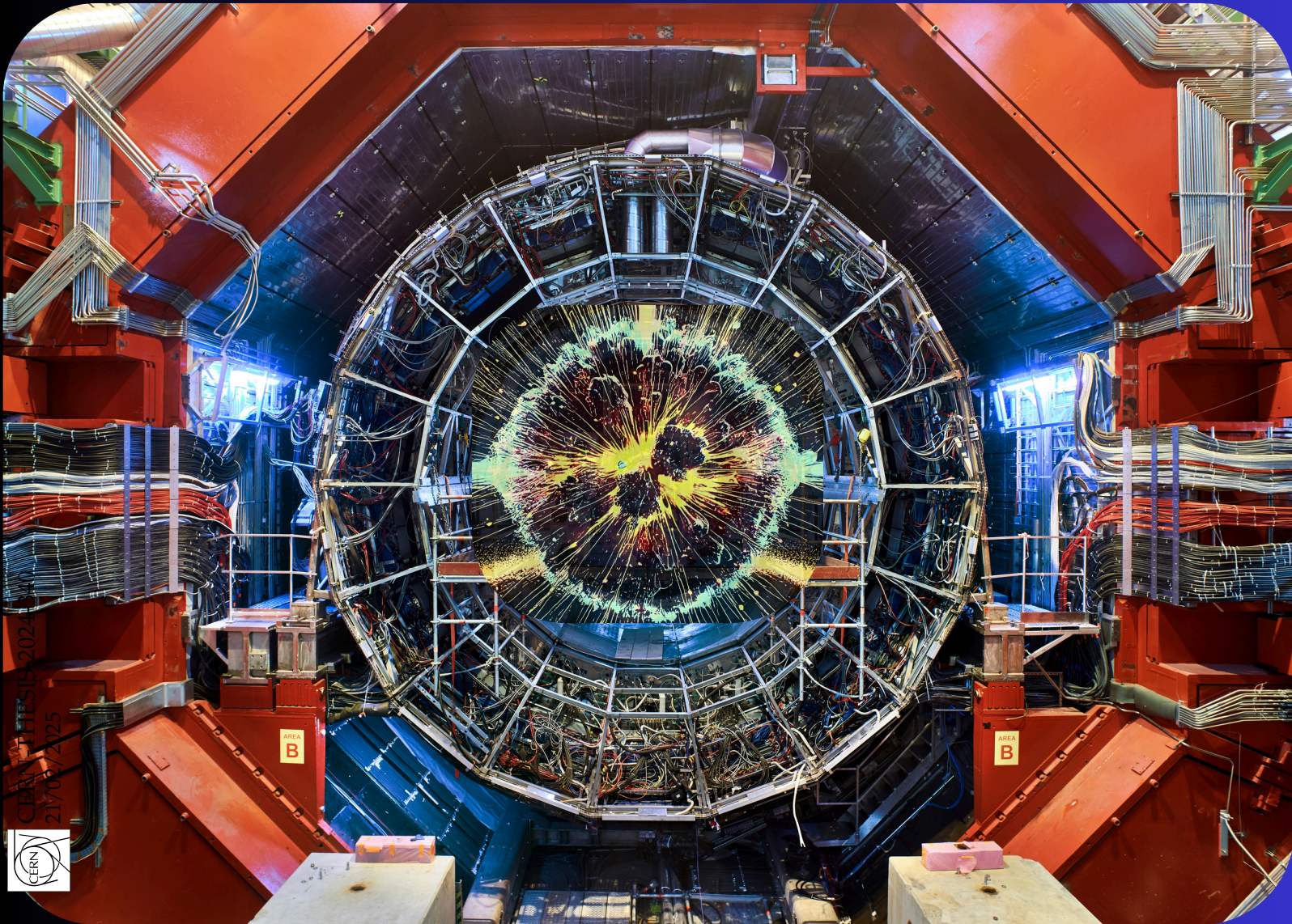


Jet energy flow fluctuations with ALICE



CERN THESIS 2024-01
21/02/2025



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Jet Energy Flow Fluctuations with ALICE

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DOI: <https://doi.org/10.33540/>

Printed by Gildeprint

Cover design by Christos Pliatskas Stylianidis



This thesis is part of the project 'Microscopy of the Quark-Gluon Plasma using high-energy probes' funded by the Netherlands Organization for Scientific Research (NWO).

Jet Energy Flow Fluctuations with ALICE

Fluctuaties in de radiële energiestroomverdeling van jets
met ALICE

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de
Universiteit Utrecht
op gezag van de
rector magnificus, prof. dr. H.R.B.M. Kummeling,
ingevolge het besluit van het College voor Promoties
in het openbaar te verdedigen op
vrijdag 21 februari 2025 te 10.15 uur

door

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geboren op 27 november 1993
te Thessaloniki, Griekenland

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Dit proefschrift maakt deel uit van het project 'Microscopy of the Quark-Gluon Plasma using high-energy probes' dat is gefinancierd door de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)

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Part I

Introduction & Theory

1 Introduction

This first chapter of the dissertation serves as an introduction to the general theoretical background which supports this research project. An outline of the dissertation structure is given in Sec. 1.1. Sections: 1.2 and 1.3 address the theoretical framework of modern particle physics and the definition of jets respectively. With a transition to high energy nuclear physics, Sec. 1.4 introduces the evolution stages of heavy-ion collisions and the medium of deconfined matter which is created in that environment. Lastly, this introductory chapter concludes with the definition of some of the experimental variables employed in the relativistic nuclear physics in Sec. 1.5.

1.1 A brief introduction

In the ever-expanding tapestry of the cosmos, human curiosity serves as the guiding beacon illuminating the intricate dance of particles and forces. Particle physics, with its relentless pursuit of the fundamental constituents of existence, embodies our innate desire to decipher the underlying fabric of reality. Grounded in the robust framework of the scientific method, particle physicists embark on a journey of discovery, melding theoretical ingenuity with experimental prowess to unlock the secrets of the subatomic realm. This collaborative endeavor, where theorists sculpt elegant narratives of the universe's workings and experimentalists harness cutting-edge technologies to unveil its hidden truths, underscores the symbiotic relationship at the heart of scientific exploration. Yet, beyond its intellectual allure, particle physics resonates deeply with society, offering profound insights into the cosmos and fueling technological innovation that transcends disciplinary boundaries, shaping our understanding of the universe and our place within it. The aim of the research presented in this dissertation is to contribute to this journey of discovery.

This thesis can be divided into five parts based on the research aspect which is being addressed. Part. I includes the current chapter and Ch. 2. The aim is to provide a solid foundation of the scientific background by providing a brief description of the theoretical framework of modern particle physics and the necessary concepts for the interpretation of this dissertation. Switching to the experimental side, Part. II describes the detector setup (Ch. 3), the software tools (Ch. 4) and the data collections (Ch. 5) which made this dissertation possible. Part. III introduces the titular topic of this thesis starting from the over-arching physics research sub-field (Ch. 6), to the observable definition (Ch. 7) and the strategy (Ch. 8) that was followed in this analysis. The results of the measurement in JEWEL simulations (Ch. 9), proton-proton (pp) (Ch. 10) and lead-ion (Pb-Pb) collisions (Ch. 11) along with their relevant comparison (Ch. 12) and discussion (Ch. 13) comprise Part. IV. Finally, a summary of this research and the options for future follow-up studies (Ch. 14) make up Part. V of this dissertation.

1.2 The Standard Model and Quantum Chromo-Dynamics (QCD)

In our current best understanding there are four fundamental forces in nature. Three of those: the electromagnetic, the weak and the strong interaction can be described by a relativistic quantum field gauge theory with the humble name of the Standard Model (SM) [1]. The fourth fundamental interaction that is not included into the SM is the gravitational force. Despite the scientific community's best efforts, a complete quantum theory of gravitation has not been developed yet. Each of the forces within the SM is mediated by a gauge boson, a particle with integer spin, that interacts with elementary particles which carry the corresponding charge.

Starting from the electromagnetic interaction, its gauge boson is the massless photon γ which interacts with electrically charged particles. The electromagnetic force is the one within the SM that is mostly encountered in daily life. The weak force facilitates the radioactive beta decays and its processes are less probable than the electromagnetic ones. The weak interaction takes place between particles that carry the flavor charge. The propagators of the combined theory of weak and electromagnetic forces (electroweak theory) are the three massive gauge bosons $W^\pm$ and Z and the photon γ . The force carrier of the strong interaction is the massless gluon g which interacts with particles that carry "color" charge. The strong interaction and its description is of particular significance for this thesis so a description of its attributes will be revisited later in this section as well as in subsequent chapters. In more technical terms, the interactions in the Standard Model are described by the local gauge symmetry $SU(3)_{color} \times SU(2)_{flavor} \times U(1)_{charge}$.

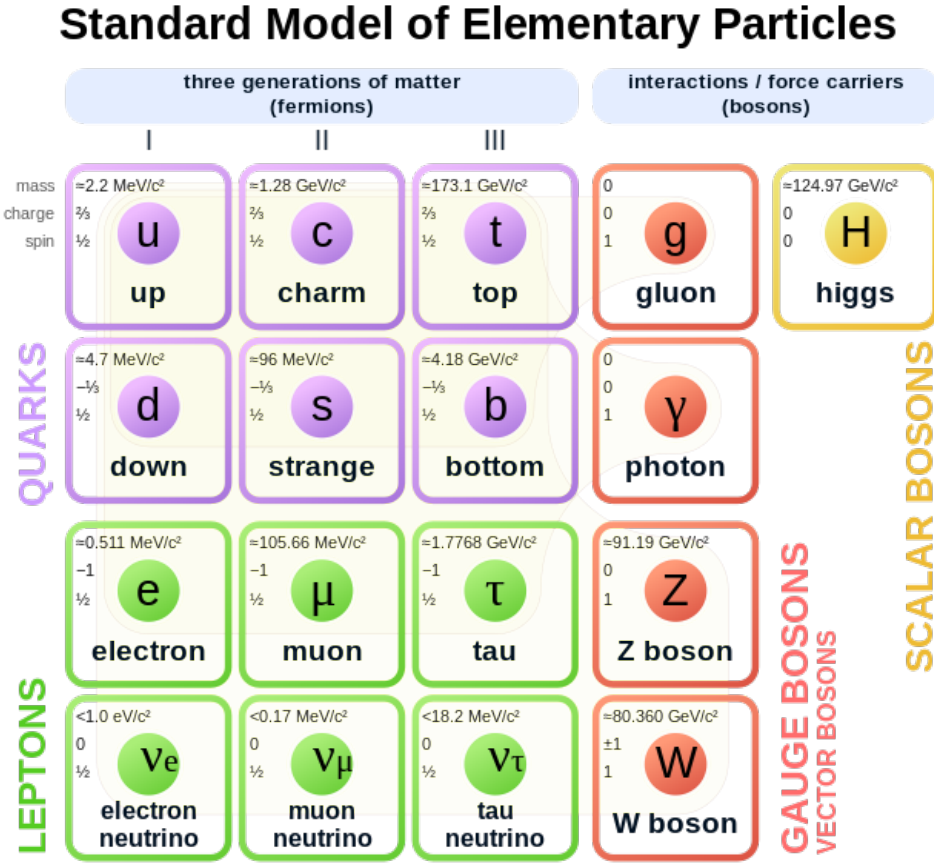


Figure 1: Chart of the elementary particles for matter and fundamental forces within the Standard Model.

The three fundamental interactions described in the previous paragraph influence the behavior of twelve elementary fermions i.e. particles with half-integer spin. These fermions can be divided into two groups: six quarks and six leptons. The six quarks participate in all three forces and are usually denoted by the first letter of their names: (u)p, (d)own, (s)trange, (c)harm, (b)ottom and (t)op. In literature, the b-quark is also referred to as (b)eaauty quark. Based on their masses, they can be separated into three generations. The leptons also appear in three generations, each one including an extremely light neutrino ν and a charged particle (electron, muon and tau). An overview of these particle groups can be seen in Fig: 1. These twelve fermions make up all

of the ordinary "matter" that we can observe in the universe. In the SM framework, each of these fermions has a corresponding antimatter partner which carries the opposite charge. The SM becomes complete with the addition of the Higgs boson. Its experimental discovery in 2012 [2, 3] confirmed theoretical predictions [4, 5] made in the 1970s. The interaction of the fundamental particles with the Higgs field gives rise to their observed masses. An in-depth description of the SM is outside the scope of this thesis and can be found in Ref. [6].

Although the SM is a wonderful theoretical framework with excellent predictive powers, it does not account for all of the available physical observations. Importantly a description of the gravitational interaction is missing from the SM. In addition, it was recently discovered that the model only describes 4% of the observable universe. The nature of the the remaining 96%, referred to as dark matter and dark energy, is one of the biggest mysteries of modern physics [7]. Furthermore, there are aspects of the observed ordinary matter which are not entirely understood such as neutrino oscillations, the matter-antimatter asymmetry and the strong CP problem. There are proposed extensions of the model to account for these phenomena but so far none of the Beyond-the-Standard-Model (BSM) theories have been confirmed experimentally. An overview of the missing puzzles from the SM and the attempts to solve them can be found in Ref. [8].

The topic of this thesis refers to the dynamics of the strong interaction and therefore a closer examination of that force is required. Within the SM, the strong force is described by the quantum field theory of Quantum Chromo-Dynamics (QCD). This theory describes the interactions between the elementary particles that carry the color charge. The only color-charged fundamental particles are the quarks and gluons commonly referred to as partons, since they were initially conceived as "parts" of the nucleons, protons and neutrons. A detailed mathematical description of QCD can be found in [9, 10]. Instead, a qualitative review of the theory's main features is given here. These features become more salient when they are presented in comparison with Quantum Electro-Dynamics (QED) [11], the quantum field theory of the electromagnetic force. In short QCD can be seen as a more complicated expanded version of QED. One of the similarities between the two theories is that their gauge bosons, the photon and the gluon, are both massless. However, while QED has only one type of charge, QCD has three types of color charge: red, green and blue. Similar to QED, color charge is conserved in QCD interactions and quarks can carry one of the three color charges. In contrast to the electromagnetic theory where photons are neutral, gluons carry unbalanced color charges and in that way enable color change between interacting partons. The fact that gluons carry color charge allows for gluon self-interactions and is a distinct feature of QCD as a non-Abelian theory. In other words, the most elementary QCD interactions occur between: i) two quarks and a gluon, ii) three gluons and iii) four gluons.

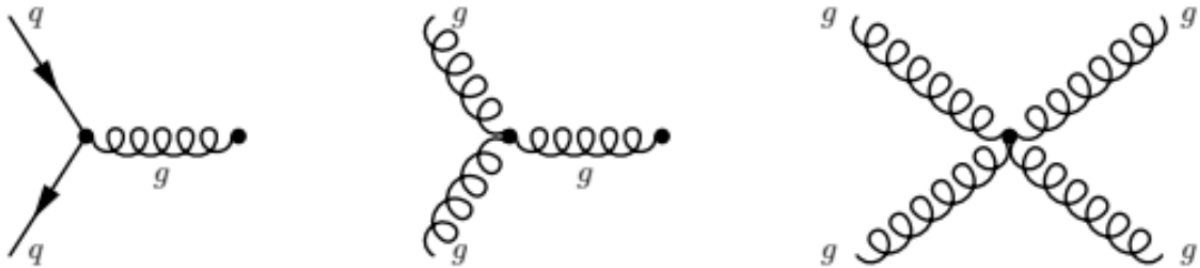


Figure 2: Fundamental Feynman vertices of QCD interactions.

Feynman diagrams are pictorial representations of interactions between the fundamental par-

ticles and can be used to calculate the cross-sections of these processes. The diagrams of the fundamental QCD vertices are shown in Fig. 2. These vertices can be combined to produce the leading order QCD interactions. These parton interactions are classified as either elastic ($2 \rightarrow 2$) or inelastic ($2 \rightarrow 3$) scatterings. Both classes of these processes are described by the Feynman diagrams (and their 90° rotated counterparts) presented in Fig. 3 and 4.

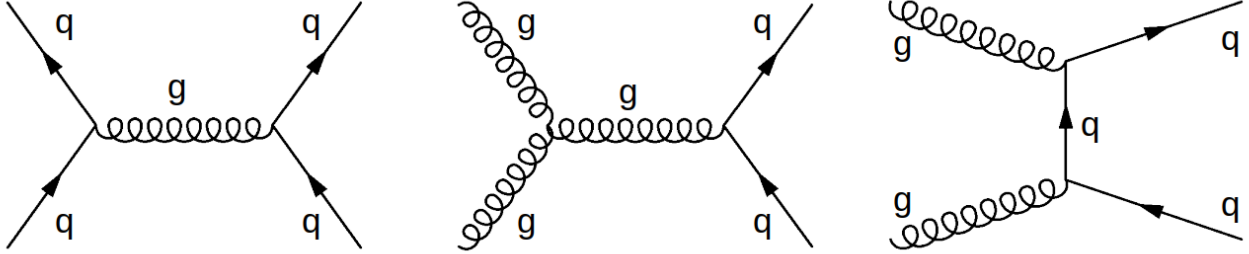


Figure 3: Leading order Feynman diagrams involving (anti-)quarks.

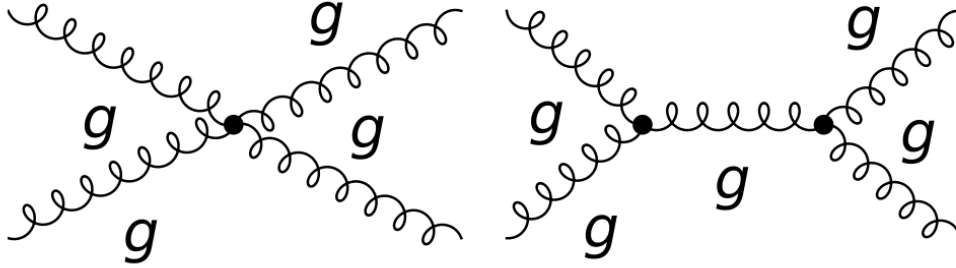


Figure 4: Leading order Feynman diagrams between gluons.

As it was mentioned above, gluons carry color charge and therefore couple with other gluons. The possibility of self-interactions leads to the anti-screening effect. To understand this effect, it is useful to first examine the charge screening effect in QED. In the simple example of photon propagation in vacuum, there is a possibility for the photon to produce virtual electron - positron pairs which are then annihilated back to a photon. In quantum field theory the interactions between particles are defined as the sum of all the possible processes. In addition, the space around electrons is occupied by virtual photons emitted from the charged particle. These photons can be treated as virtual electron-positron pairs. The pairs will be aligned in a way that the positrons are closer compared to the virtual electrons to the parent electron. In this way the negative electric charge of the electron is shielded or "screened" by the accumulated positive charge of the virtual positron population. This screening effect leads to the weakening of the electromagnetic force as a function of distance.

The same effect exists also in QCD, where color charge is screened by the color charge of antiquarks in the virtual quark - antiquark pairs. As it was mentioned above, gluons can couple with other gluons so it is possible to have a production of a virtual gluon pair. However, the different color structure of the gluons enhances rather than shields the charge of the source as a function of the distance. This anti-screening effect is dominant over the screening mechanism in QCD. This fact follows from the calculation of the beta function for the $SU(3)$ symmetry which describes

QCD and turns out to be negative. Due to the anti-screening effect, the coupling constant for the strong interaction a_s behaves differently than the QED coupling constant as a function of distance. These effects can be visualised with the first-order Feynman diagrams depicted in Fig: 5.

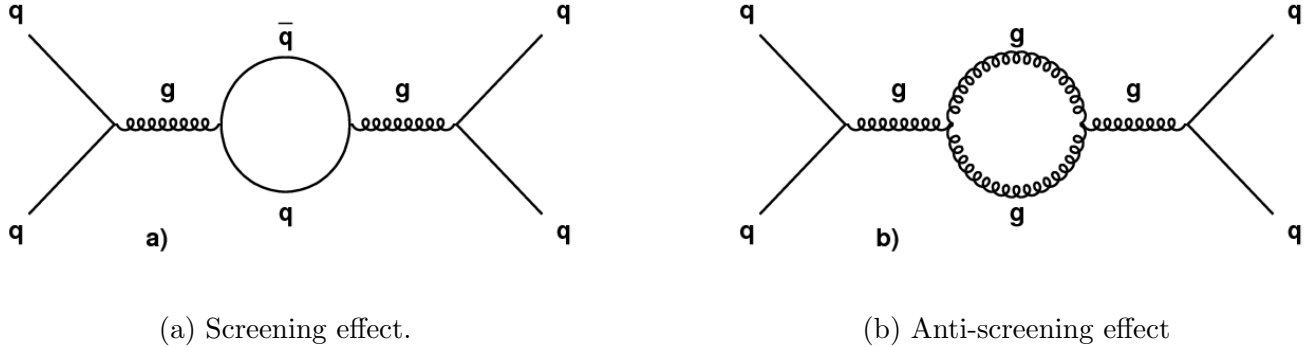


Figure 5: Representations of the screening (left) and anti-screening(right) effects in QCD with first-order Feynman diagrams [12].

This behavior of the running coupling constant leads (Fig: 6) to two unique phenomena in QCD: asymptotic freedom [13] and color confinement [14, 15]. At very short distances, or equivalently high momentum exchanges (Q^2) between partons, the strong coupling constant becomes small and the participating partons behave as quasi-free particles. On the contrary, at long distances or low-energy interactions of the partons, the coupling constant becomes very large. Although a rigorous mathematical proof has not been achieved, it is suspected that the large magnitude of the strong coupling constant leads to the confinement of the partons inside color-neutral hadronic states. Because of the significant variation of the coupling constant, the theoretical treatments differ in the two energy regimes. At sufficiently high energies ($Q^2 \gg 1 \text{ GeV}^2/c^2$), calculations can be performed using a perturbative expansion in terms of α_s (pQCD). In the low-energy regime, the magnitude of α_s does not allow for a perturbative approach and effective theories or numerical approaches are used instead. The most famous of these approaches is Lattice QCD (lQCD) [16–18] with which non-perturbative calculations are performed on a discrete space-time grid. Lattice QCD has been remarkably successful in the description of the properties of hadrons produced in collider experiments [19].

1.3 Jet production in hadronic collisions

A large fraction of modern particle physics research takes place in hadron collider experiments. In a high-energy hadronic collision, for example between two protons, the particles that participate in the scattering are not the protons as a whole but their parton constituents. If there is considerable momentum transfer then the interaction between the colliding partons is referred to as hard scattering. In the majority of these scatterings, the highly energetic products of this process that fly away from the interaction point are also partons. These particles carry the strong color charge so they can emit gluons which in turn can split into quark-antiquark pairs or undergo gluon emission themselves. As a result, each of the outgoing hard partons produces a shower of softer particles through gluon radiation QCD emissions or quark pair production. As the energy of the individual particles decreases, perturbative QCD can no longer describe their behavior because the strong coupling constant becomes very large. At that stage, partons become confined as quark-antiquark pairs (mesons) or triplets of either quarks (baryons) or anti-quarks (antibaryons).

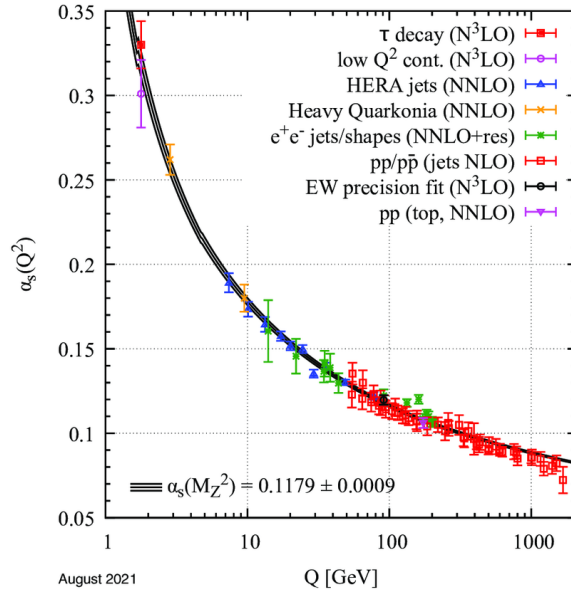


Figure 6: A summary of experimentally extracted values of the strong coupling constant as a function of the momentum transfer compared with QCD calculations [20].

In other words, the partons fragment non-perturbatively into color-neutral states (hadrons). This stage of the interaction is referred to as hadronisation and its results correspond to the particles that are detected by the experimental apparatus. The collimated spray of particles emerging as the result of the parton shower can be clustered together in so-called "jets". The algorithms that are employed towards that end are revisited later in this section.

A schematic picture of a hard scattering is available in Fig: 7. Qualitatively the process can be divided into three stages: the initial state, the hard scattering itself and the final state. This separation is based on the factorisation theorem which relies on the separation of long and short distance QCD processes [21]. It is worth mentioning that the factorization theorem is widely accepted in the scientific community however a rigorous mathematical proof has not yet been reached for all of the QCD processes.

In the initial state of the hard scattering, the kinematics of the colliding partons are described by the Parton Distribution Functions (PDFs). These functions ($f_{a/A}(x, Q^2)$) encode the probability of finding a parton of a given flavor a with momentum fraction x inside the colliding hadron A . In the case of nuclear collisions, these probabilities are modified and described by nuclear PDFs (nPDFs) instead. The determination of these functions and their modification in the case of nuclei constitutes a research field in its own right.

The hard scattering itself is described by the cross section of the colliding partons $\sigma(x_1, x_2, Q^2)$ which can be calculated using pQCD. The scattering cross section depends on: a) the dynamics of the interaction which is encoded in a matrix element and b) the available kinematic phase space which is described by the density of states [22]. These interactions cause the partons to emit and absorb gluons, a process detailed by the splitting functions, which describe how a parent parton splits into multiple offspring partons, initiating a parton shower. As time progresses, the energy scale of the interactions changes, and the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations [23–25] come into effect. These equations dictate how the PDFs evolve as a function of the energy scale. Eventually, the high-energy partons lose energy and undergo fragmentation, breaking apart into a cascade of lower-energy particles. This process is described by

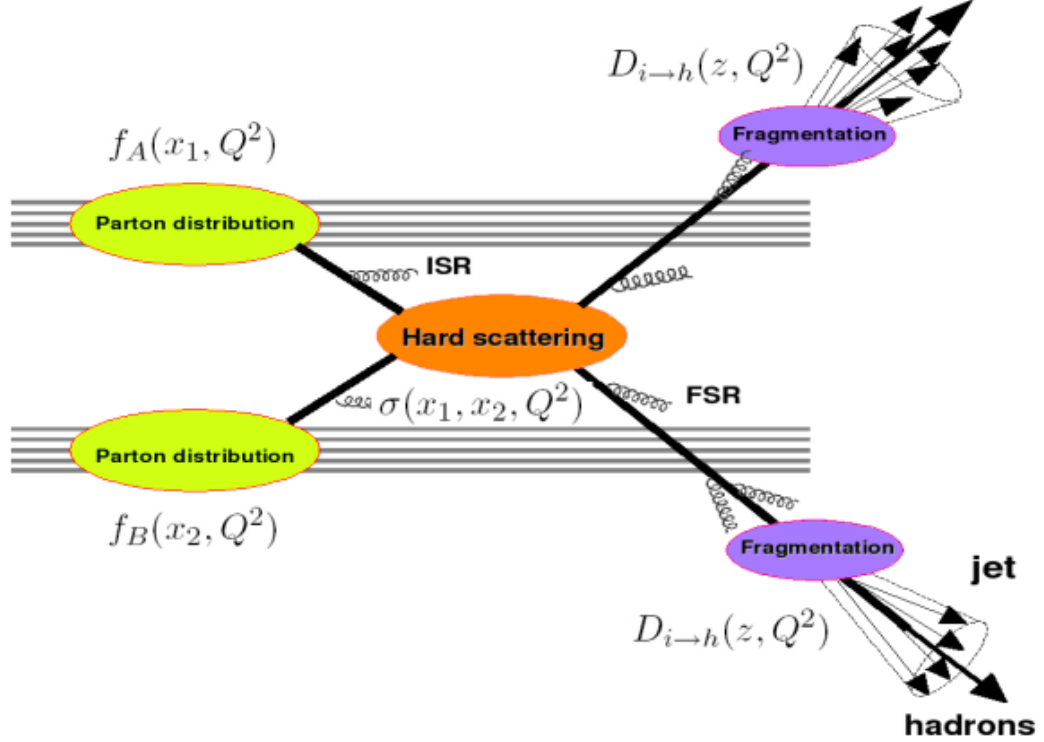


Figure 7: A schematic of di-jet production in a hadronic collision with the main components of the factorisation theorem [21]

the non-perturbative fragmentation functions (FF) $D_{p \rightarrow h}(z, Q^2)$ which determine the probability that an outgoing parton p fragments, in a final hadron h with momentum fraction z . The evolution of the FF as a function of the energy scale is also described by the DGLAP evolution equations. Furthermore, as can be seen in Fig: 7, it is possible to have QCD radiation both in the initial (ISR) as well as in the final state (FSR).

The partonic hard scattering cross section with the two non-perturbative components described above can be convoluted to calculate the cross section for the production of high energy hadrons,

$$d\sigma_{AB \rightarrow h}^{hard} = f_{a/A}(x_1, Q^2) \otimes f_{b/B}(x_2, Q^2) \otimes d\sigma(x_1, x_2, Q^2) \otimes D_{c \rightarrow h}(z, Q^2). \quad (1)$$

This way of calculating cross sections is motivated by the QCD factorisation theorem [26], which states that the interference between long- and short-distance processes ('higher twist') is suppressed by factors $1/Q^2$. In simpler terms the validity of the factorisation theorem relies on the separation of long and short distance QCD processes [21].

The partonic constituents of the parton shower are not experimentally accessible since detectors retrieve information at the hadronic level. However, clustering algorithms applied on the collimated spray of hadronic states that reach the detector provide access to the parton shower. The experimental objects defined with these algorithms are called jets and they probe the initiating hard parton of the shower. A comprehensive review of the most popular candidates and their performance can be found in Ref. [27]. For the purposes of this introduction it suffices to say that jet clustering (or jet finding) algorithms can be separated in two broad categories: i) cone algorithms and ii) sequential recombination algorithms.

Cone algorithms define jets by clustering particles within a cone of a fixed radius in the rapidity-

azimuth plane, with the cone's axis pointing in the direction of the jet's momentum. They are conceptually simple and computationally efficient. However they exhibit issues with respect to infrared and collinear safety, a concept which will be explained at the end of this section. In addition, cone algorithms may have difficulties in defining stable jet boundaries in complex event topologies, leading to ambiguities in jet identification and measurement. A jet cone algorithm that stands out is the *SisCone* algorithm [28]. *SisCone* is infrared and collinear safe and characterised by improved stability and accuracy of jet boundaries. *SisCone* provides more reliable jet reconstruction in complex events.

Sequential algorithms operate in the momentum space and cluster particles in jets based on their transverse momenta and angular separation. Initially, this class of algorithms was plagued by slow computational performance but later developments have resolved this issue. A useful feature of sequential algorithms is that they intrinsically define a cluster sequence of particles which approximates the probabilistic picture of the parton branching [27]. In addition, one distinctive feature of these algorithms is that the resulting jets have non-circular areas reflecting the natural spread and complexity of the particle distributions within jets.

The most widely used sequential algorithms are the inclusive *k_t* algorithm [29, 30], the Cambridge/Aachen (C/A) algorithm [31, 32] and the anti-*k_t* algorithm [33]. A comparison of the clustering sequences found by each algorithm is shown in Fig: 8.

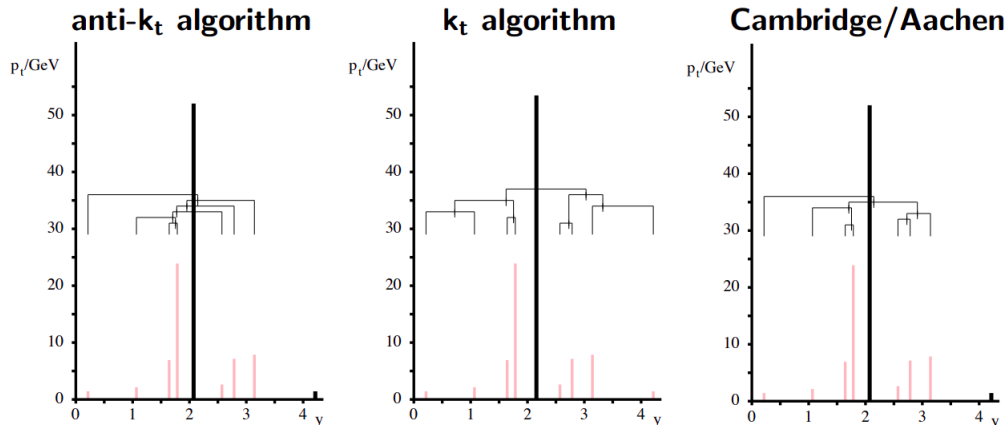


Figure 8: Overview of the jet clustering scheme for the *k_t*, anti-*k_t* and C/A algorithm [34].

The three sequential clustering algorithms follow a similar procedure and use two distance variables. The first variable is the distance d_{ij} between two particles i and j ,

$$d_{ij} = \min(p_{T,i}^a, p_{T,j}^a) \frac{\Delta R_{ij}^2}{R^2}. \quad (2)$$

The choice of the exponent parameter a distinguishes the three algorithms. The free parameter R is called the jet radius or resolution parameter. It defines a cone around the jet axis and serves as a cut-off parameter. ΔR_{ij} corresponds to the distance between the two particles in the rapidity-azimuth plane,

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2. \quad (3)$$

The second distance variable is d_{iB} ,

$$d_{iB} = p_{T,i}^a \quad (4)$$

is the momentum space distance between the beam axis and the detected particle i . The algorithm relies on the iterative comparison between the variable d_{ij} and $d_{i,B}$. Specifically it follows these steps:

1. Calculate all d_{ij} and $d_{i,B}$
2. Find the minimum of the d_{ij} and $d_{i,B}$
3. If $d_{ij} < d_{i,B}$ cluster the two particles together into a single new particle and return to step 1.
4. Alternatively if $d_{ij} > d_{i,B}$, the i particle is defined as a jet. Remove it from the particle list and return to step 1.
5. Stop when there are no remaining particles.

At this point, the role of the R parameter in the jet definition becomes clear: if a particle i has no other particles within a distance R then its $d_{i,B}$ will be smaller than d_{ij} for any j and the i particle will then be declared as a jet.

The parameter a distinguishes the three jet finding algorithms. The inclusive kt algorithm corresponds to $a = 2$ and clusters soft particles first. The C/A algorithm uses $a = 0$ and prioritizes pairs of particles with the smallest distance ΔR_{ij} for recombination. The clustering sequence of the C/A algorithm maintains an angular ordering which can be useful for jet substructure studies. Lastly, the anti-kt algorithm corresponds to $a = -2$ and clusters the hardest particles first. This algorithm also leads to jets with mostly circular areas.

Two important attributes for jet finding algorithms are the so-called infrared and collinear safety (IRC). IRC safe algorithms are resilient with respect to collinear splittings and soft gluon emissions in the sense that they lead to the same amount of hard jets in the presence of such effects [27]. The robustness of the algorithms to the effect of soft non-perturbative QCD processes allows the comparison between the theoretical predictions and experimental measurements. The IRC safety definition can be extended to jet observables (Sec. 1.5) translating to the insensitivity of the measurements to soft and collinear emissions. Lastly, it has been shown that some IRC unsafe observables can still be calculated through the use of non-perturbative objects like PDFs and fragmentation functions. These observables are called "Sudakov safe" since the technique relies on the use of a Sudakov form factor for the re-summation. A theoretical derivation and explanation of Sudakov safety is given in Ref. [35].

1.4 The Quark Gluon Plasma

It is evident from the description of a proton-proton collision (pp collision) in the preceding section that a full microscopic description of the process is highly non-trivial. The level of complexity is increased even further in the investigation of high-energy collisions between nuclei or more specifically between ions of heavy elements. In these events, the number of colliding nucleons and by extension the number of participating partons in the collision is vastly larger than in a pp collision. Therefore, heavy-ion collisions serve as an excellent testing ground to investigate the behavior of nuclear matter in a high energy density environment. Furthermore, the conditions of extreme density and temperature achieved in these collisions simulate the early stages of the universe shortly after the Big Bang in a smaller scale. These investigations connect the physics of the microcosm explored through particle physics with the cosmological macrocosm. This connection highlights the exciting prospects of the research field.

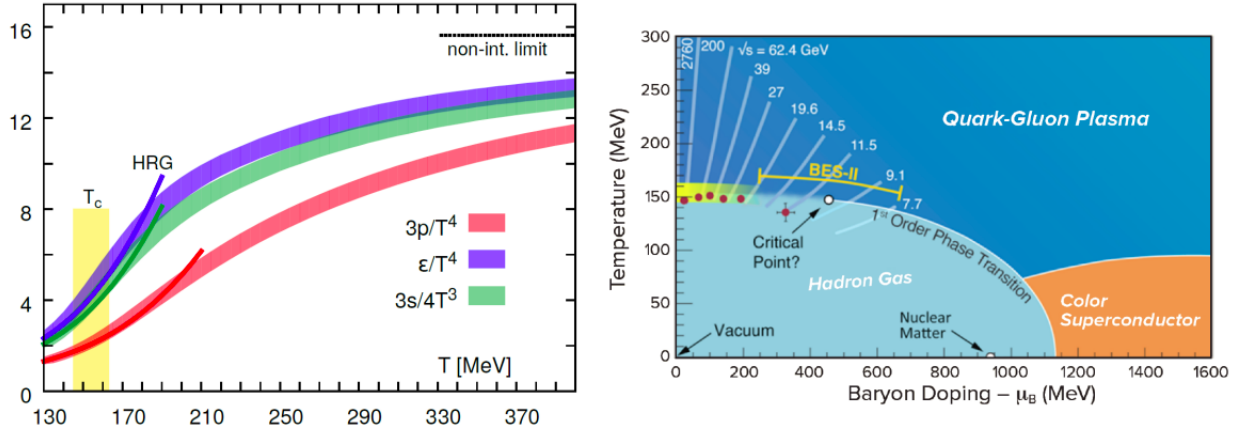


Figure 9: **Left:** Lattice QCD calculations for the temperature dependence of pressure (red) and energy density (blue) normalized to the fourth power of the temperature. The dependence of the entropy density (green) normalized to the third power of the temperature is also plotted. The dashed line on the upper right corner corresponds to the non-interacting Stefan-Boltzmann limit. A smooth transition from a hadron resonance gas (HRG) to a Quark Gluon Plasma state around the critical temperature $T_c \approx 150$ MeV is also shown [36]. **Right:** The QCD phase diagram as a function of temperature (T) and baryo-chemical potential (μ_B). For the details of the state of matter depicted in this map see Sec. 1.4 as well as the Ref. [37]

At the microscopic level, the interactions between the nucleons in heavy-ion collisions translate to interactions between the partons. These are strong force interactions described by the theory of QCD. As it was described in Sec. 1.2, the theory predicts a strong variation of the coupling constant as a function of the energy or distance scale at which matter is probed. Additionally, from a thermodynamic standpoint, the nuclear matter produced in these collisions can be studied as a function of energy density or temperature. An equation of state formulates this description and the relation between the medium properties. Lattice QCD calculations about the dependence of pressure, energy and entropy density on temperature for a medium with zero net baryon density can be seen in Fig. 9. These quantities are normalized to the fourth (or third for entropy density) power of the temperature. This normalization originates from the thermodynamic Stefan-Boltzmann law which describes the dependence of total energy density radiated by an ideal gas. In that plot it can be seen that as the temperature increases, the energy and entropy density experience a smooth cross-over transition around the temperature of $T_c = 150$ MeV. This corresponds to a transition from a hadron resonance gas state (HRG) to a new state of matter. This new state has more thermodynamic degrees of freedom than HRG and resembles a medium of deconfined quarks and gluons. Such a deconfined state is referred to as Quark Gluon Plasma (QGP).

In physics, transitions between different states of matter are typically depicted in phase diagrams. A schematic picture of our understanding for the QCD phase diagram can be seen in Fig. 9. The vertical axis corresponds to the temperature while the horizontal axis represents the baryo-chemical potential which is related to the excess of quarks over anti-quarks. Heavy-ion collisions at very high energies lead to the production of thousands of particles with an approximate balance of quarks versus anti-quarks (i.e. $\mu_B \approx 0$). Therefore the upper left region of the QCD phase diagram is probed in those relativistic energy collisions. On the other hand, in experiments that operate at lower energies, the production of particles is smaller and the abundance of quarks in the colliding

nuclei leads to larger baryo-chemical potential. The region in low temperatures and extremely high baryo-chemical potential is expected to exhibit color superconducting properties. Although these conditions are beyond the reach of particle colliders, environments with high baryon doping exist in the core of neutron stars. However, it is not clear whether color-superconductivity is achieved in those conditions. The smooth crossover transition at low baryo-chemical potential is also shown in the plot in the region of the critical temperature T_c . Based on the symmetries satisfied by QCD a first order phase transition (critical point) at higher μ_B is expected but this prediction has not been confirmed by the experiment so far.

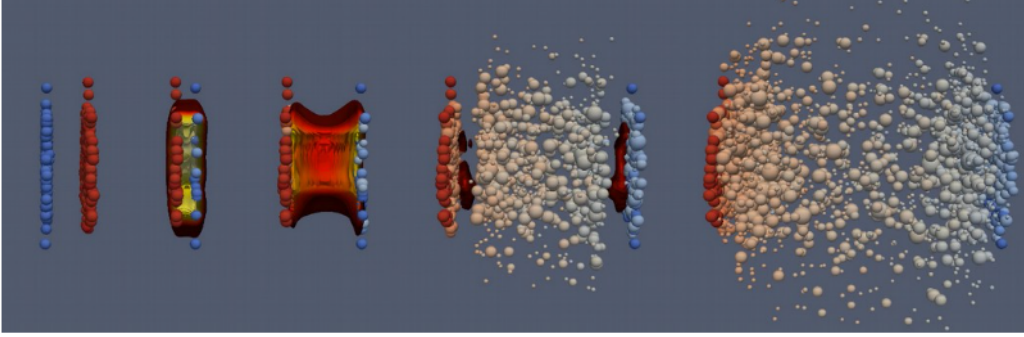


Figure 10: A schematic diagram depicting the evolution stages of a heavy-ion collision [38].

The diagram in Fig: 10 depicts snapshots in time of the evolution stages in a heavy-ion collision. Starting from left to right, these stages can be divided as:

- **Initial state:** This is the left-most picture of Fig: 10 and corresponds to the last moment right before the collision. Due to the acceleration at relativistic energies, the nuclei are Lorentz contracted in the centre-of-mass frame resembling two colliding disks. The initial state is described by the nuclear PDFs of the partons inside the nuclei. In a simplified view, the colliding nucleons are composed of three valence quarks, gluons and a "sea" of quark-antiquark pairs. Based on this description, the interactions mostly take place between gluons with a low longitudinal momentum fraction. These interactions are relatively soft with small momentum transfer and therefore generate only a small amount of transverse momentum. Since these soft gluons represent the majority of the colliding partons, understanding their behavior can elucidate the dynamics of the early stages of the deconfined QCD medium. In fact, many bulk observables which are related to the medium transport coefficients exhibit a large sensitivity to the properties of the initial state. A more detailed review of the open research questions in this field is included in Ref. [39, 40].
- **Pre-equilibrium:** The exact moment of the collision is the stage with the highest energy density as a result of the Lorentz contraction. At that moment the medium is far from equilibrium and therefore this stage is referred to as pre-equilibrium or early stage. The scattering processes with large momentum transfers (hard processes) take place in this stage. Based on this description, the pre-equilibrium stage is the origin of the so-called hard probes, like jets, direct photons and heavy quarks. As time progresses, softer interactions with small Q^2 interactions also take place in the context of a weakly coupled pre-equilibrium phase. The softer partons gradually enable the formation of a strongly coupled QGP phase. With interactions becoming more frequent, the medium transitions to a thermal equilibrium allowing its description in terms of temperature. A review of the dynamics describing this stage of the

collision can be found in [40, 41]. Recently, a practical framework was introduced, connecting the pre-equilibrium stage to the subsequent thermodynamic evolution of the medium [42, 43].

- **Quark Gluon Plasma:** As the produced medium of deconfined matter approaches thermal equilibrium, its constituent partons continue to interact strongly with each other. Once equilibrium is achieved, the medium starts to expand and cool down as it is depicted in the third snapshot of Fig: 10. Due to the rapid expansion, thermal equilibrium is only achieved locally. In addition, the anisotropies of the initial density distribution lead to a spatial and temporal dependence of the temperature. The QGP has a temperature above the critical temperature T_c and undergoes a phase transition as it continues to cool down. Understanding the dynamics which govern the evolution of the QGP is one of the main goals of heavy-ion physics research. The macroscopic evolution of the medium can be modeled with relativistic fluid dynamics [44, 45]. Using this description, it has been found that the QGP exhibits a very low shear viscosity η/s approaching the expectations for a perfect liquid [46].
- **Hadronisation:** The medium continues to expand and cool down until its local temperature drops below the critical temperature. This crossover transition marks the start of hadronisation where the partons become confined in color-neutral particles. The confinement process takes place locally and it is expected that the abundances of most particle species are defined in this stage which is referred to as chemical freeze-out. Even after the phase transition, the medium behaves as a hot hadron gas and its behavior can be described by thermodynamic parameters. The newly formed gas is still dense and in a state of local thermal equilibrium due to the interactions between its hadron constituents. As time progresses and the expansion of the gas continues, the medium eventually becomes sufficiently dilute so that hadrons cease their interactions. This transition is referred to as kinetic or thermal freeze-out. Afterwards, the particles stream freely towards the detector. The mechanisms that govern the non-perturbative hadronisation process are not fully understood and their relative contributions are an open debate topic within the scientific community. The two primary proposed hadronisation mechanisms are fragmentation and coalescence. Fragmentation processes [47–49] have been used in the past to describe the relatively simpler pp collisions and they have been adapted for the case of heavy-ion collisions. Another proposed mechanism for hadronisation is coalescence [50, 51]. According to the coalescence or recombination mechanism, quarks and antiquarks that are near each other in phase space combine to form hadrons. Coalescence is more dominant in environments where the density of quarks and antiquarks is high.

From the above discussion it should be evident that a description of a heavy-ion collision and the evolution of the QCD medium produced in these collisions involves multiple stages. The extremely short lifetime of the medium (of the order of a few femtoseconds) impedes further its experimental investigation. The particles that interact with the detector are hadrons which are not identical to the partons that make up the QGP. However, objects defined on a collection of hadrons, such as jets (Sec. 1.3) represent the initiating partons in the collision. Particularly, since the initiating partons of the jets are produced in the early stage of the collision their parton showers witness the entire evolution of the medium. Due to these characteristics, jets can be treated as probes of the QGP since the constituents of their parton shower interact with the medium. A direct consequence of the interaction with the medium is the induced energy loss of the hard partons (Sec. 2.2). Of course, jets are not the sole experimental probes of the QCD medium. Heavy flavor hadrons as

well as quarkonium ($Q\bar{Q}$ states) are all seen as hard probes of the QGP. The category of hard probes also includes photons, W and Z bosons produced in the heavy-ion collision which can serve as control measurements since they do not carry color charge and therefore do not interact with the QCD medium. A schematic overview of these probes and the information that can be extracted for the medium parameters can be seen in Fig: 11.

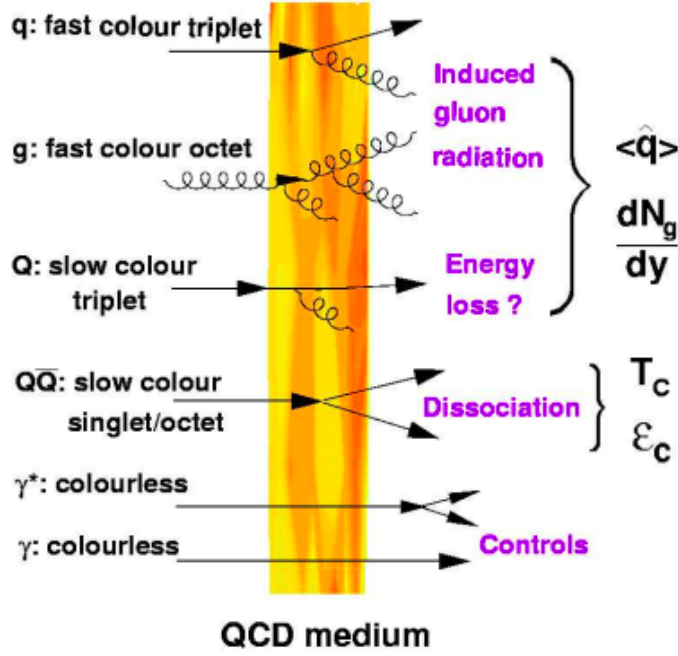


Figure 11: Modification of hard probes by the medium produced in heavy-ion collisions can shed light on the QCD matter properties such as the critical temperature and energy density [52].

Lastly, even though the production of the QGP can not be observed directly, its presence can be deduced by its signature on the experimental observables. These observables extend to objects which do not necessarily fit the definition of hard probes. A comprehensive review of all the predicted QGP signatures and the devised experimental measurements to confirm them lies outside the scope of this introduction and this dissertation. The interested reader is encouraged to study the detailed reviews presented in Ref. [53–55]. With that caveat and for the sake of completeness in this introduction, two noted experimental measurements which support the production of the QGP in a heavy-ion collision are: the anisotropic flow [56–59] and the observation of strangeness enhancement [60, 61].

1.5 Experimental observables

In lieu of an exact definition for what constitutes an experimental observable, it can be safely approximated as a variable which can be calculated with quantities that are accessible at the reconstructed level. Since these quantities can be measured with the detector apparatus, they correspond to information available at the hadronic level.

A good example, are the kinematic variables which describe the orbits of the detected particles. This description can be condensed into a four-vector $p^\mu = (E, p_x, p_y, p_z)$ where E and p_i correspond to the energy and momentum of the particle in each of the three orthogonal axes respectively. In

collider experiments, the most commonly used variables are the transverse momentum $p_T = p_x^2 + p_y^2$ and the pseudorapidity $\eta = -\ln(\tan(\theta/2))$ where θ is the angle between the vertical y-axis and the direction of the particle. The set of coordinates in the three dimensions becomes complete with the azimuthal angle ϕ between the x-axis and the direction of the particle. By convention the z-axis corresponds to the beam axis. Pseudorapidity is preferred over the polar angle θ because particle production has been found to be relatively constant with respect to this quantity.

Measurements reveal the laws of nature but this interpretation requires the comparison of the experimental results with theoretical predictions. If the observable corresponds to a variable which can be calculated directly from the principles of the underlying theory, then a straightforward comparison with these calculations is an ideal scenario. However it is possible that a direct comparison is not possible either due to the complexity of the calculation or the investigated system or due to an incomplete mathematical description of the theory in the relevant kinematic regime. In those cases, Monte Carlo simulations of the experimental measurement can breach the gap. These models are derived from theoretical calculations and principles and rely on random sampling from an event population which follows specific probability distributions. Comparison of experimental measurements, once they are corrected for detector effects, with model predictions is a staple component of modern physics research.

In the realm of QCD, the concepts of infrared and collinear safety presented in Sec. 1.3 are invaluable for the comparison between theory predictions and experimental measurements. Infrared and collinear safe observables ensure the reliability of comparisons between the theoretical calculations performed at the perturbative high energy regime with the experimental measurements which often include soft and collinear emissions. Finally, comparisons for infrared and collinear safety observables allows for interpretations with high accuracy and precision.

2 Parton energy loss

After the introduction of the over-arching theoretical framework in Ch. 1, the focus of this chapter is on the theory which describes the behavior of quarks and gluons. Quantum Chromodynamics (QCD) is the quantum theory which describes the strong force. The parton interactions within the framework of QCD are presented in Sec. 2.1. In heavy-ion collisions, the interactions of the medium constituents with the partons resulting from hard scattering are described in Sec. 2.2. Medium interactions lead to a loss of energy for the hard scattering partons and an account of the theoretical formalisms to calculate these processes is given in Sec. 2.3. Studies of these processes probe the properties of the QGP medium and its strong interaction dynamics.

2.1 QCD processes and parton interactions in vacuum

In pp collisions, the interaction of the colliding high energy partons can be visualized as a scattering of partons (quarks and/or gluons) through a gluon exchange or annihilation and subsequent pair production. The initial partons produced from the hard scattering undergo a series of gluon emissions, quark-antiquark pair productions and gluon splitting, which result in a branching cascade of particles with progressively decreasing energy. In this radiation pattern, color coherence [62] between the emission sources is significant as it leads to angular ordering effects. In order to understand this effect it is instructive to examine the coherence effect between splitting emission in the "simpler" case of pair production in QED (Fig. 12).

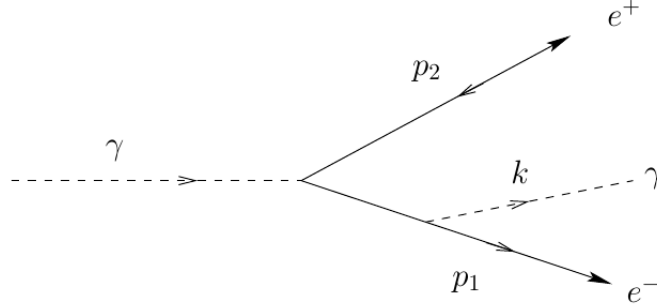


Figure 12: Schematic of bremsstrahlung radiation after pair production of electron pair [63].

To investigate the extent that the produced electron and positron emit independent photons it is useful to consider the required time interval for a photon radiation from an electron branch. This interval is called formation time and is estimated as [63],

$$t_{form} \approx \frac{1}{k\Theta_{\gamma e}^2}, \quad (5)$$

where $\Theta_{\gamma e}$ is the angle between the electron and the emitted photon. Furthermore $k\Theta_{\gamma e} = k_{\perp} = \lambda_{\perp}^{-1}$ with $\lambda_{\perp}$ the transverse wavelength of the radiated photon. So Eq. 5 can be expressed as

$$t_{form} \approx \frac{\lambda_{\perp}}{\Theta_{\gamma e}}. \quad (6)$$

During this formation time, the transverse separation of the lepton pair is estimated as,

$$\rho_{\perp}^{e^+e^-} \approx \Theta_{e^+e^-} t_{form} \approx \lambda_{\perp} \frac{\Theta_{e^+e^-}}{\Theta_{\gamma e}}. \quad (7)$$

Therefore, for large angle emissions of photons $\Theta_{\gamma e} \gg \Theta_{e^+e^-}$, the transverse wavelength of the emitted photon is larger than the separation of the two emitters. In this case, the internal structure of the splitting is not resolved by the photon and instead it probes the total electric charge of the parent, which is zero. As a result, emissions where $\Theta_{\gamma e} \gg \Theta_{e^+e^-}$ are strongly suppressed. In the antenna approximation, the $\rho_{\perp}^{e^+e^-}$ sets a length scale so that emissions from the electron and positron can be treated independently only if $\rho_{\perp}^{e^+e^-} > \lambda_{\perp}$ which is satisfied when $\Theta_{\gamma e} < \Theta_{e^+e^-}$.

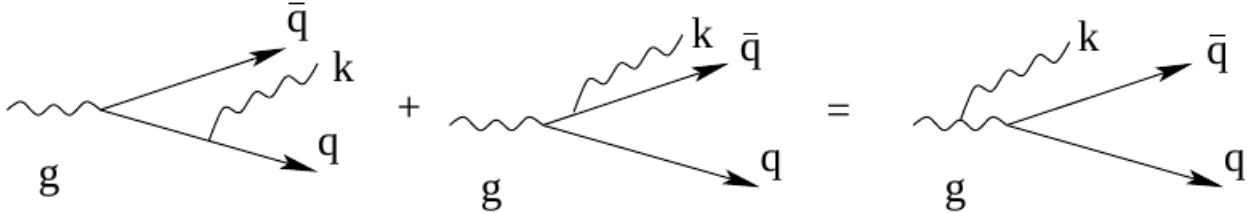


Figure 13: Wide angle emissions of a soft splitting are equivalent to an emission from the parent parton [63].

Returning to the realm of QCD, the same picture holds for gluon cascades where color is conserved in the splittings (Fig. 13). Contrary to the QED case, the coherent radiation of a soft gluon from an unresolved pair of quarks is not zero but instead it is equivalent to an emission from the parent gluon [64]. This is a universal property which holds also for $q \rightarrow qq$ and $g \rightarrow gg$ splittings. This phenomenon of *intrajet* color coherence translates to the dependence of successive emissions on the preceding branching. This leads to a suppression of wide angle emissions and gives the parton shower in vacuum an angular ordering (AO) feature, i.e. a monotonic decrease of successive opening angles in the cascade [65, 66].

2.2 Parton interactions in the Quark Gluon Plasma

In high energy nuclear collisions, a state of deconfined matter is produced where its constituents carry the QCD color charge. The presence of this medium modifies the parton shower compared to pp collisions (*vacuum case*). When the partons produced in the collision traverse such a medium, they interact with its constituents. These interactions modify the parton shower through medium-induced gluon emissions or diffusion due to elastic scatterings [67]. The phenomenon of these modifications, as it is probed through experimentally reconstructed jets, is referred to as *jet quenching*. A description of the experimental characterisation of jet quenching is provided in Ch. 6. The present section focuses on the theoretical description of the modified shower at the parton level.

Elastic scatterings of the incoming hard parton as well as its emitted gluon with the medium constituents lead to parton energy loss (Fig. 14). There are both radiative and collisional energy loss mechanisms, with medium-induced radiation becoming more dominant at higher energies. The radiative energy loss induced by scatterings inside a medium of a given length is characterised by the transport coefficient,

$$\hat{q} = \langle k_T^2 \rangle / \lambda, \quad (8)$$

which represents the mean transverse momentum squared acquired by the incoming particle per mean-free path [67]. The distribution of emitted gluons depends on the parton energy, the medium

density and the strength of the interactions. For emissions at small scattering angles, the incoming parton and the radiated gluon propagate along similar paths. This effect leads to larger formation time for the emitters. The simultaneous presence of multiple emitters inside the medium, due to successive scatterings for example, makes interference effects important. The interference between those emitters suppresses the gluon radiation compared to the incoherent scenario of independent emissions. This effect is referred to as the Landau-Pomeranchuk-Migdal [68, 69] effect and was initially formulated in the context of QED. Due to the LPM effect, the radiative energy loss scales quadratically with the path-length in the medium, if those distances are small compared to the finite formation time [70]. From a perturbative description, a few different formalisms have been developed to describe the radiation pattern. A brief description of those, their similarities and differences is given in the next section of this chapter.

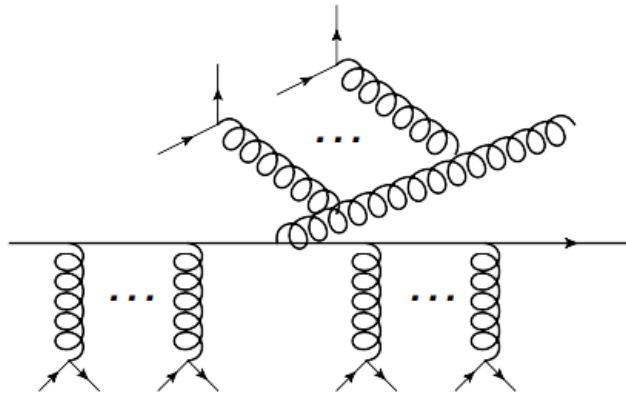


Figure 14: Schematic of single gluon emission in-medium through elastic scatterings with the medium constituents [67].

The quark-antiquark antenna picture introduced in the vacuum case is also useful to understand the effect of color coherence between the medium-induced gluon emissions. QCD bremsstrahlung radiation similar to the vacuum case with its characteristic angular ordering pattern still takes place as the parton transverses the medium. However, in the medium case a new transverse length scale Λ_{med} is introduced which characterizes the color correlation length within the medium. If the separation of the two antenna partons is smaller than Λ_{med} , then the individual emitters are not resolved by the medium and the pair undergoes coherent energy loss as a single emitter. On the other hand, if the medium resolution length is shorter than the antenna separation, then they are resolved by the medium and treated as individual emitters. This scenario enhances gluon radiation leading to a broader parton shower and larger energy loss of the propagating parton. This effect lifts the restriction of the gluon emissions to increasingly smaller angles and it is referred to as anti-angular ordering [71]. The medium coherence length introduces a limit for the consideration of individual emissions as independent. In that regard, based on the formation time and medium resolution length, the LPM effect can lead to either suppression or enhancement of gluon radiation [67]. All of these individual components and their interactions need to be considered in order to understand the in-medium gluon radiation. Further details can be found in Ref. [62, 64, 71–73].

Parton energy loss through elastic processes is characterised by the longitudinal momentum loss and diffusion. At a leading approximation these scatterings can be described through $2 \rightarrow 2$

processes. Collisional energy loss is quantified by the elastic energy loss rate or drag,

$$\hat{e} = \frac{dE}{dt} . \quad (9)$$

Drag can be calculated through pQCD or lQCD and lends insight on the thermalization process of partons in the medium. Collisional energy loss is particularly significant at low and intermediate energies for the heavy-flavor partons which have larger mass [67].

2.3 Theoretical formulations of parton energy loss

At high energies, parton energy loss predominantly takes place through radiative processes. An initial calculation of the radiated spectrum for a single gluon was derived within the path-integral formalism developed by Baier-Dokshitzer-Mueller-Peigne-Schiff [74–76] (BDMPS) and independently by Zakharov [77–79]. Two semi-analytical treatments of the BDMPS-Z formalism operating in limiting approximations are commonly considered:

- The hard scattering limit, which assumes few interactions of the parton with the medium with considerable momentum exchange. This formalism was derived by Gyulassy-Levai-Vitev [80–83] (GLV) using an expansion in terms of the number of scattering centers: the opacity expansion. The formalism has been extended to include dynamical scattering centers in the medium by Djordjevic [84] (DGLV).
- The limit where the parton has multiple soft interactions with the medium. In these approximations the number of scattering centers is very large and the medium is fully characterized by the transport coefficient $\hat{q}$ (Eq. 8). Work by Armesto, Salgado and Wiedemann [85–88] (ASW) in this limit lead to the calculation of ‘quenching weights’ which represent the energy loss probability distribution. In literature this approximation is referred to as ASW-MS, since a calculation of quenching weights is also available for the case of a single hard scattering (ASW-SH).

An alternative formalism to the case of multiple soft scatterings which treats the medium as weakly-coupled and in thermal equilibrium, was developed by Arnold-Moore-Yaffe [89–93] (AMY). In the approximation of an infinite length for the medium, the propagators are modified by the medium through thermal interactions via a hard-thermal-loop (HTL) potential. Since the medium is no longer treated as a collection of static scattering centers, this formalism can include both collisional and radiative energy loss. Later developments of this approach addressed the infinite length limitation [94].

A fourth approach computed in the kinematics regime of Deep Inelastic Scattering (DIS) provides higher-twist radiative correction to the inclusive cross section. This Higher-Twist [95–100] (HT) formalism assumes a dilute medium with few scatterings, usually a single hard scattering. Energy loss calculations based on the HT approach were pioneered by Guo and Wang [95, 96]. Generalizations of the formalism to hold for multiple scatterings have also been developed [101].

The above formalisms are characterised by a strong ordering of the momentum and energy scales between the incoming parton, the emitted gluon and the medium constituents. Particularly, the propagating parton’s and emitted gluon’s energy are considered larger than the exchanged momentum. As a result, the propagating particles follow eikonal trajectories. Generalization beyond eikonal effects and finite energy corrections have been introduced in recent years. Specifically, numerical approaches to generalize the calculations of the BDMPS-Z/ASW and DGLV formalisms

have been made, offering a full resummation in the number of scattering centers [102, 103]. In the case of AMY, the initial assumptions of instantaneous gluon radiation have been investigated by considering gluon emissions with finite formation time [104]. Within the HT formalism, an extension of the modified DGLAP evolution equations with induced gluon radiation has been introduced [105]. In addition, the Monte Carlo implementations which couple radiative energy loss to a dynamic evolution of the bulk medium in real time have been developed [106]. All of these approaches address single gluon emission.

Multiple gluon emissions inside the medium and their interference is a very important step towards the interpretation of experimental jet measurements. The modifications to the spectrum of the quark-antiquark antenna, which was described in the previous section have been described within the BDMPS-Z/ASW formalism. The coherence effects between the multiple medium scatterings have been investigated within this formalism. Furthermore, similar to the AMY recipe, the rate equation for multiple in-medium branchings within a finite medium assumes instantaneous gluon emissions. The transition from single to multiple gluon emissions in most approaches assumes that the number of gluons emitted along a given path follows a Poisson distribution. This approximation allows the calculation of the parton energy loss by integrating the single emission probability provided by each formalism. However, these calculations neglect the dynamic evolution of the medium and the gradual energy degradation of the incoming parton through the interactions. This last feature can lead to total energy loss greater than the parton's initial energy. This scenario can be interpreted as the absorption of the particle from the medium. With respect to the dynamic evolution of the medium, it has been shown that in the multiple soft scattering limit [88, 107], a relation between a static scenario and an arbitrary dynamic expansion can be established through a scaling law. However these approximations result in significantly different quenching parameters [107]. This disagreement highlights the important effect of an expanding medium on the jet transport coefficients.

In all of these approaches, coherence effects between subsequent emitters have been considered negligible. To explore coherence effects, a two-gluon configuration with separate formation times has been investigated as a correction to the previous picture of incoherent radiation between different emitters [108]. Medium-induced emissions are characterised by small formation times so that the effects of finite formation times are usually discarded.

In order to compare the theoretical predictions to experimental jet measurements, the above prescriptions for single gluon emission are implemented in Monte Carlo generators [109–112]. In the cases where analytical calculations are not available, MC simulations offer important higher-order corrections to the parton shower and the option to include the parton shower development through the lifetime of the QGP. Through the development of the parton shower, the constituents become progressively softer so that the energy and the medium response to their propagation can be treated with transport models. In some models, the medium response is treated hydrodynamically after local thermalization while in others it is approximated as recoil particles. All of the theoretical treatments detailed previously are valid within the regime of perturbative QCD. When the particles reach energy scales in the order of the QGP temperature, the weakly coupling approach is no longer applicable. There have been holographic calculations using the AdS/CFT correspondence to study energy loss in a strongly coupled medium [113]. A MC model which is based on such an approach with respect to energy loss is the Hybrid model [114].

To describe collisional energy loss, as mentioned earlier, the DGLV formalism has been expanded to include dynamic scattering centers. Also, the HT formalism has extensions that allow the inclusion of longitudinal drag and diffusion. In terms of MC generators, an alternative approach are jet transport codes which monitor all of the propagating particles and include diffusion.

Examples of such transport codes are MARTINI [115], which uses rate equations, or Linearized Boltzmann Transport [116] (LBT), which describes parton evolution by linear Boltzmann equations. Radiative energy loss according to the AMY or HT formalism is also included in some of these models.

An in-depth review and comparison of the formalisms is available in Ref. [67, 70, 73, 117] and references therein. Lastly a review of the MC implementations of jet quenching is featured in Ref. [118].

Part II

Experimental Setup & Analysis Tools

3 The ALICE Detector

This chapter is dedicated to a concise description of ALICE (A Large Ion Collider Experiment) [119] experimental setup (Sec. 3.3) and its research goals (Sec. 3.2) after a brief introduction of the Large Hadron Collider in Sec. 3.1. The focus of Sec. 3.4 and 3.5 is on the subdetector systems which were utilised in this analysis for the track reconstruction. Lastly, Sec. 3.6 is dedicated to the determination of the collision centrality which is significant for the heavy-ion component of the measurement.

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [120] is a powerful particle accelerator and collider facility located near Geneva in Switzerland and serves as the basis of CERN. LHC is located in an underground ring tunnel with a circumference of 26.7 km. The tunnel was originally excavated to house the Large Electron-Positron (LEP) [121] collider which was the predecessor of LHC.

LHC is a synchrotron-type accelerator comprised of two superconducting ring beam lines which can accelerate protons as well as heavy-ions to very high energies. Synchrotrons are circular accelerators that increase the kinetic energy of a beam of particles while maintaining the same curvature for their orbits. This is achieved by the application of magnetic fields with increasing strength. Specifically LHC is designed to achieve collisions at center-of-mass energy $\sqrt{s} = 14$ TeV for protons and $\sqrt{s_{NN}} = 5.5$ TeV per nucleon-nucleon pair of lead nuclei (Pb^{82+}). In order to reach these collision energies the particles are accelerated in multiple facilities of increasing energy. An overview of the LHC accelerator complex with the individual circular and linear accelerator machines can be seen in Fig. 15.

For the acceleration of protons, after they are extracted from the hydrogen tank they are introduced to the linear accelerator (LINAC 2) where they reach an energy of 50 MeV. After LINAC 2, they undergo many stages of acceleration as they are subsequently injected to the Proton Synchrotron Booster (BOOSTER), Proton Synchrotron (PS), Super Proton Synchrotron (SPS) and finally to the LHC. The acceleration of ions is similar to the procedure followed for the protons. The difference lies in the first two stages of the procedure. Vaporised lead ions enter Linac 3 for the first stage of acceleration and afterwards are injected to the Low Energy Ion Ring (LEIR). LEIR not only accelerates the lead ions to higher energies but also transforms them into short, dense bunches suitable for injection at the LHC.

In the LHC ring, the two circulating beams rotate in opposite directions and they collide in four interaction points. These interaction points house the four biggest LHC experiments. The two largest experiments, ATLAS (A Toroidal LHC Apparatus) [123] and CMS (Compact Muon Solenoid) [124] are general-purpose experiments designed to study the Higgs physics sector as well as physics beyond the Standard Model. These two experiments have the same scientific goals, however their different technical solutions and magnet conditions allow for a complementary approach to their research. The LHCb (Large Hadron Collider beauty) experiment [125] specializes in the investigation of differences between matter and antimatter in beauty (or bottom) hadron decays. The ALICE experiment [119] is specifically designed to study heavy-ion collisions in order to investigate the properties of strongly interacting matter at high temperatures and densities. There are four more underground locations in the ring which are used to collimate or dump the beams.

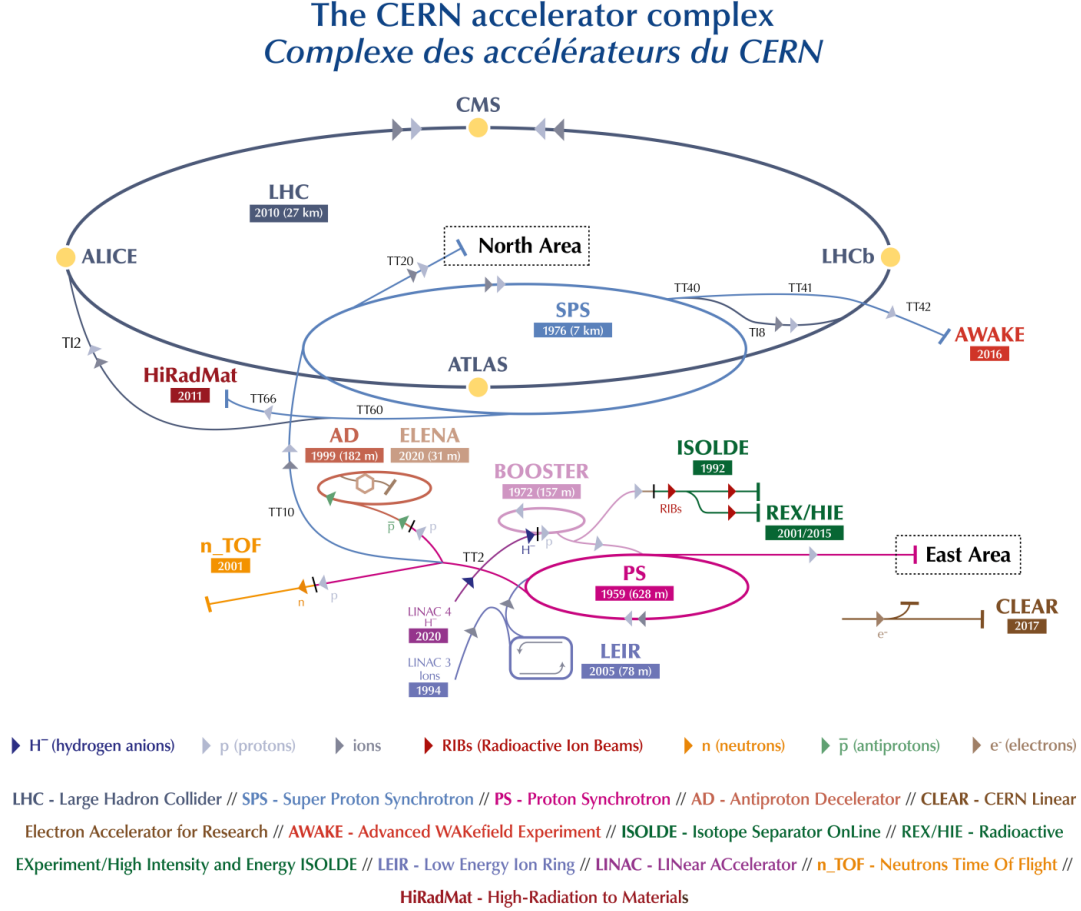


Figure 15: A schematic view of the LHC accelerator complex depicting the main accelerator facilities and experiments [122].

3.2 The ALICE research programme

All four of the major experiments at the LHC have a dedicated heavy-ion research programme. However, this field of research has been the main goal of the ALICE experiment since its conception. As described in Sec. 1.4, a medium of deconfined quarks and gluons is created in high energy collisions of nuclei. The study of the properties of this medium and interactions between its constituents is a unique testing ground for the QCD theory of strong interactions at extremely high densities and temperatures. The studies undertaken by the ALICE collaboration can shed light on the creation and evolution of the quark-gluon plasma and the mechanisms that confine quarks and gluons into the bulk of ordinary matter. The understanding of key issues such as color confinement and chiral symmetry restoration are important aspects in QCD.

In the study of deconfined matter, a broad list of probes including hadrons, electrons, muons, and photons is investigated in ALICE. The experiment also studies proton-proton and proton-nucleus collisions both as a reference for comparison with nucleus-nucleus collisions as well as in their own right. A comprehensive and in-depth description of the ALICE physics programme can be found in Ref. [53, 126, 127] and references therein. With this caveat and for introductory purposes, this section provides only a brief outline of the major topics and questions investigated by the experiment.

In Run 2 of LHC, analyses were undertaken on rare probes, such as heavy flavour particles, quarkonium states, real and virtual photons, jets and their correlations. Particularly the focus was on the coupling of these objects with the medium and the hadronisation processes. The highlights of the Run 2 ALICE physics programme include:

1. An exploration of the hydrodynamic properties of the QGP in its approximation as a liquid. The bulk properties of the medium can be extracted by studying the collective behavior of the produced hadrons.
2. An investigation of the thermalization process of partons in the QGP, with focus on the heavier, charm and bottom quarks.
3. Study of the quarkonia states as a probe of quark deconfinement. The suppression of quarkonia production in heavy-ion collisions is sensitive to the interplay of dissociation processes, regeneration patterns and cold nuclear matter effects.
4. The equation of state of the medium and the chiral nature of the phase transition as it is probed by the production of thermal photons and low-mass dileptons emitted by the QGP.
5. Jet and jet correlation studies as a probe for the in-medium parton energy-loss. In particular the dependencies of energy loss on the parton colour-charge, mass, and energy, as well as on the density of the medium are important.
6. An investigation of the strong interaction between hadrons through the study of heavy nuclear states such as hypernuclei and multi-strange baryons. Measurements of the binding energies of light antinuclei and hypernuclei produced in pp, p-Pb and Pb-Pb collision can contribute in this investigation.

These fields of study will continue to be investigated systematically with higher precision measurements in the LHC Run 3 and the experimental campaigns to follow. A continuously updated physics programme has to be accompanied by detector upgrades which will allow more accurate and novel measurements. More information on the future of the ALICE physics programme can be found in [128, 129].

3.3 The ALICE apparatus

The ALICE experiment [119] is located at the interaction point 2 of the LHC ring. The research presented in this thesis used the experimental data collected during Run 2 of the LHC. For that purpose the following detector descriptions refer to their status during the scientific campaigns of Run 1 and 2. The experimental apparatus is approximately 16 meters high, 16 meters wide and 25 meters long. A schematic overview of the experimental setup and the individual sub-detector systems can be seen in Fig. 16. According to the research goals of the experiment, the study of the quark-gluon plasma produced in heavy-ion collisions requires the ability to track particles down to low momenta in events with high particle multiplicities. In order to achieve that, the sub-detectors have high granularity and low material budget. Furthermore, the ALICE detector has an exceptional capability for particle identification which is essential for many physics investigations.

The detector can be divided into two main parts: the central barrel which cover the central rapidity region ($|\eta| < 0.9$) and the muon spectrometer in the forward region ($-4 < \eta < -2.5$). The central barrel includes the Inner Tracking System (ITS) and the Time Projection Chamber (TPC)

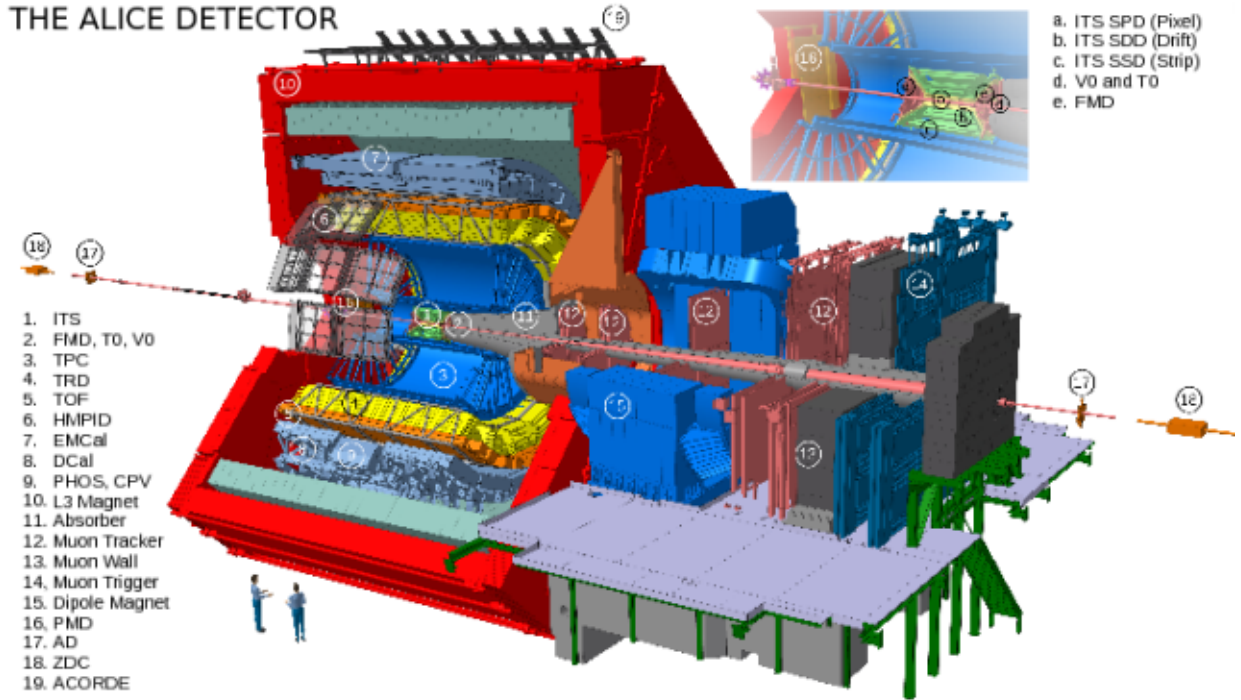


Figure 16: A schematic overview of the ALICE apparatus and its subdetector components [130]. A zoomed-in view of the inner central barrel is featured in the top right corner of the figure.

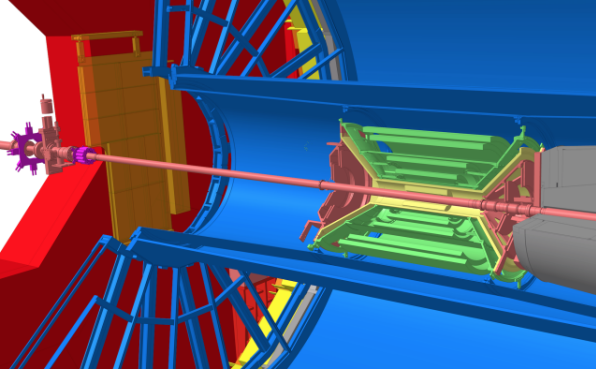
both of which play a vital role in the collection of data analysed in this thesis. The characteristic red L3 magnet encompasses the central barrel and provides a magnetic field of $B = 0.5$ Tesla parallel to the beam line. A combination of information from the different sub-detectors, allows the determination of the production point, the kinematic characteristics and identification of the produced particles. For charged particles, which are the primary ingredients in this analysis, the aim is to use tracking detectors to identify their trajectories. By applying an external magnetic field with the L3 magnet, the particle trajectories are bent, so the transverse momentum of the particle can be derived by their curvature. Particularly the charged particles which traverse the detector without decaying interact with specific sub-detectors like the ITS, the TPC, the Transition Radiation Detector (TRD) and the Time Of Flight (TOF). The trajectories of the neutral particles are not affected by the magnetic field so their detection is achieved through their energy deposition at the calorimeters which surround the central barrel. The following sections are dedicated to the sub-detectors employed in this analysis while a detailed discussion of the ALICE detector performance can be found in Ref. [131–133].

3.4 Inner Tracking system

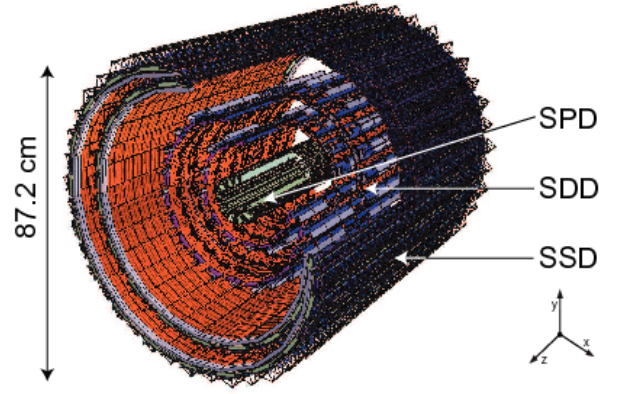
In the heart of the ALICE detector's central barrel lies the ITS [134] which can be seen in Fig. 17a. It is composed by six silicon layers which provide full coverage in the azimuth range and the central pseudorapidity region ($|\eta| < 0.9$). When charged particles traverse through the ITS, their interactions are registered as hits at the sub-detector's layers. The combination of hits in multiple layers is essential for the track reconstruction.

The primary purposes of ITS are:

1. the determination of the primary vertex position



(a) ITS lies in the heart of central barrel in the ALICE detector [130].



(b) ITS is a cylindrical six-layer detector equipped with three different silicon technologies.

Figure 17: Schematics of the ITS during the Run 2 of LHC.

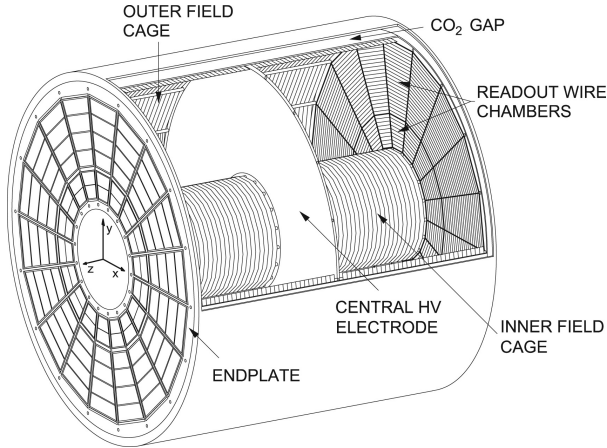
2. the reconstruction of secondary vertices necessary for the study of heavy flavor decays
3. the tracking and identification of low momentum particles
4. the improvement of momentum and angle resolution for the particles reconstructed by the TPC

As it can be seen in Fig. 17b, ITS is equipped with three different silicon technologies with two layers for each of them. The two innermost layers closest to the beam line use Silicon Pixel Detectors (SPD). The SPD layers are placed closest to the beam line because of their high resolution and fast response. The first attribute is used for the reconstruction of weakly decaying heavy flavor particles, while their fast signals are used to trigger on particle multiplicity in the mid-rapidity region. The next two layers are equipped with Silicon Drift Detectors (SDD) which can cope with high track densities. The outermost layers of the detector use double-sided Silicon Strip Detectors (SSD), and they are essential for the propagation of reconstructed tracks between the ITS and TPC tracking subdetector. Determination of the energy loss per unit path-length through dE/dx measurements [135] in the SDD and SSD layers enables particle identification operations. A truncated mean is applied to the measurements, that is, an average of the lowest two is taken if all the four layers gave a signal, or a weighted average is taken if only three are available.

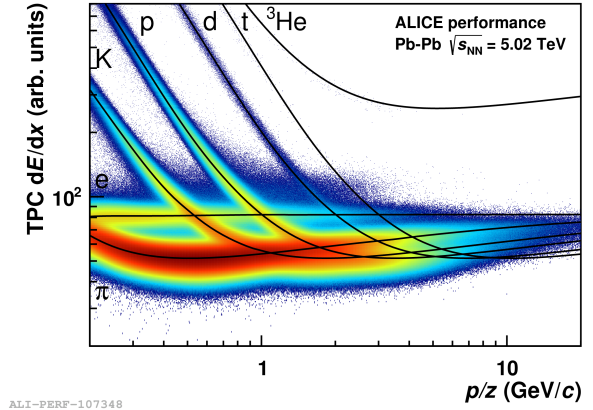
3.5 Time Projection Chamber

The TPC [136] is the main tracking detector of the central barrel, an illustration of its main components can be seen in Fig. 18a. The TPC is a cylindrical gas detector with the same coverage in azimuth angle and rapidity as the ITS. Its primary function is track reconstruction and particle identification. It is a detector optimised to provide excellent momentum resolution in a large range from 100 MeV/c up to 100 GeV/c in a high multiplicity environment. The chamber is filled with a gas mixture of either neon (Ne) or argon (Ar) with carbon dioxide (CO_2) and nitrogen (N_2). As charged particles traverse the gas, they ionise it, producing free electrons which then drift towards the end caps of the detector due to the application of an external electric field. Multi-wire

proportional chambers with cathode pad readouts, divided into 18 trapezoid sectors are mounted on the plates of the end-caps. Near the anode wires, the produced free electrons collide with the gas molecules and ionise them, producing electrons at an accelerated rate. Through this avalanche effect the initial free electron signal is amplified at the readout chambers. The two-dimensional position of the hit on the end cap plate combined with the drift time information are used to reconstruct the tracks in three dimensions.



(a) A schematic illustration of the TPC detector and its main components [136].



(b) A dE/dx measurement demonstrating the particle identification capabilities of TPC.

Figure 18: A schematic view of the TPC detector (left) accompanied by a characteristic measurement of the energy loss per unit path-length, dE/dx , as a function of the magnetic rigidity p/z . (right), where p is the particle momentum and z its charge in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV during Run 2. Comparisons with the expected curves of seven particle species are also included.

TPC also plays a very important role in the particle identification of the reconstructed tracks. This capability is based on the measurement of the energy loss per unit path-length dE/dx for the charged particles that transverse the detector. This rate of energy loss, described by the Bethe-Bloch formula [20, 135], depends on the charge, momentum and mass of the particle. The dE/dx for each track is determined from the 65% lowest amplitude clusters assigned to it. This approximation is sufficient because the produced particles are characterized by very asymmetric radiation spectra with long tails (Landau distributions). In ALICE, a parameterization of the Bethe-Bloch formula with five parameters fitted to the data [131] is used. As it can be observed in Fig. 18b, the levels of agreement between the measured energy loss and the theoretical prediction vary as a function of the momentum. The classification of the particle species is clearer towards lower momenta, while there is significant overlap between the curves as the momentum increases. At higher momenta this overlap does not allow the distinction of the different particle species. As an example, a good discrimination between charged pions and kaons can be performed up to $p \leq 0.7$ MeV/c where the largest separation is observed. The excellent particle identification capabilities of the TPC are one of the distinctive features of ALICE.

3.6 Centrality determination

The ALICE detector has multiple systems which can be used to measure the total amount of particles produced in a collision, which is referred to as event multiplicity. While the SPD layers

of ITS are sometimes used to provide a large acceptance in pseudo-rapidity, the most accurate measurement is provided by the full tracking system, consisting of the ITS and TPC. An additional complementary measurement can be carried out with the detector that is installed as two sub-detectors at very forward and backward rapidities. This latter system is V0 [137, 138], a scintillator detector comprised by V0A with rapidity coverage $2.8 < \eta < 5.1$ and V0C which covers $-3.7 < \eta < -1.7$. Each of the two V0 stations has 32 channels and is segmented in four rings in the radial direction, with 8 sectors in the azimuth angle. The total amplitude of the coincidence signal in the V0A and V0C is proportional to the event multiplicity.

The V0 detector fulfills multiple roles such as triggering, rejection of beam-gas collisions and of course determination of event multiplicity and collision centrality. As a trigger, the coincidence of signals in V0A and V0C defines the minimum bias trigger which was used in the analysis presented in this thesis. In addition, the coincidence requirement in the two V0 arrays reduces the background from single diffractive interactions. In Pb-Pb collisions, selections on the V0 multiplicity are used to discriminate between central and semi-central collisions as well as to define the corresponding triggers.

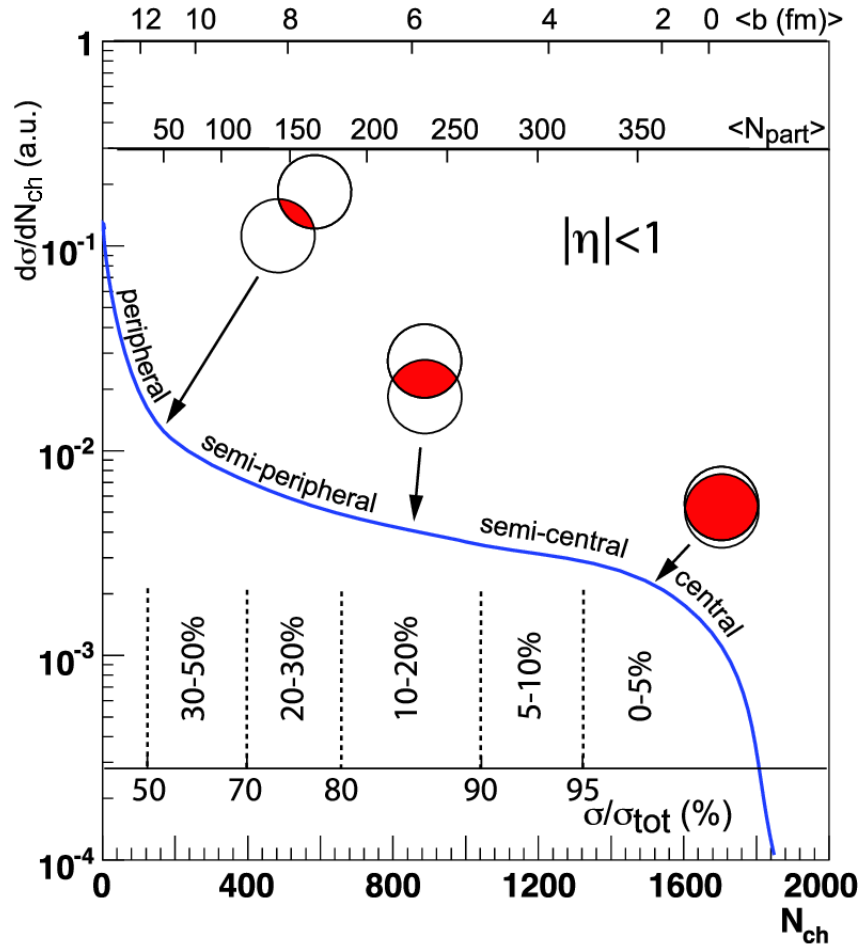


Figure 19: Multiplicity distribution for charged particles. The horizontal axis illustrate the correspondence between the impact parameter, the charged particle multiplicity and the number of participants [139].

An important concept in heavy-ion collisions is the centrality of the collision, or the amount of overlap between the two colliding nuclei. The impact parameter b is the distance between the

centers of the two colliding nuclei. The most central collisions where the overlap in the collision zone is largest are characterised by a small value of the impact parameter. Collisions where there is small overlap in the collision zone are called peripheral. Fig. 19 includes sketches of the overlap in the collision zone and their relation to approximate values of the impact parameters. The shape of the overlap in the collision zone and the density of participating partons (*participants*) are defined by the centrality. In central collisions there are more participants ($\langle N_{part} \rangle$) compared to the peripheral case. The indirect relation between $\langle N_{part} \rangle$ and the multiplicity of charged particles produced in the collision, N_{ch} is also shown in Fig. 19. It has been found that there is a monotonic relation between these two quantities [139].

Experimentally, the impact parameter cannot be accessed directly and the multiplicity is used as a measure of centrality instead. Results are reported in percentile bins of the multiplicity, with e.g. the 0 – 5% centrality representing 5% of events with the highest charged particle multiplicity. The 5% with the next highest multiplicity are defined as 5 – 10% centrality and so on. The centrality definition takes advantage of the monotonic relation between the hadronic cross section and event multiplicity. Due to the fluctuations of the measured charged particle multiplicity, the proportionality to the impact parameter is satisfied better for intervals of 5% and higher.

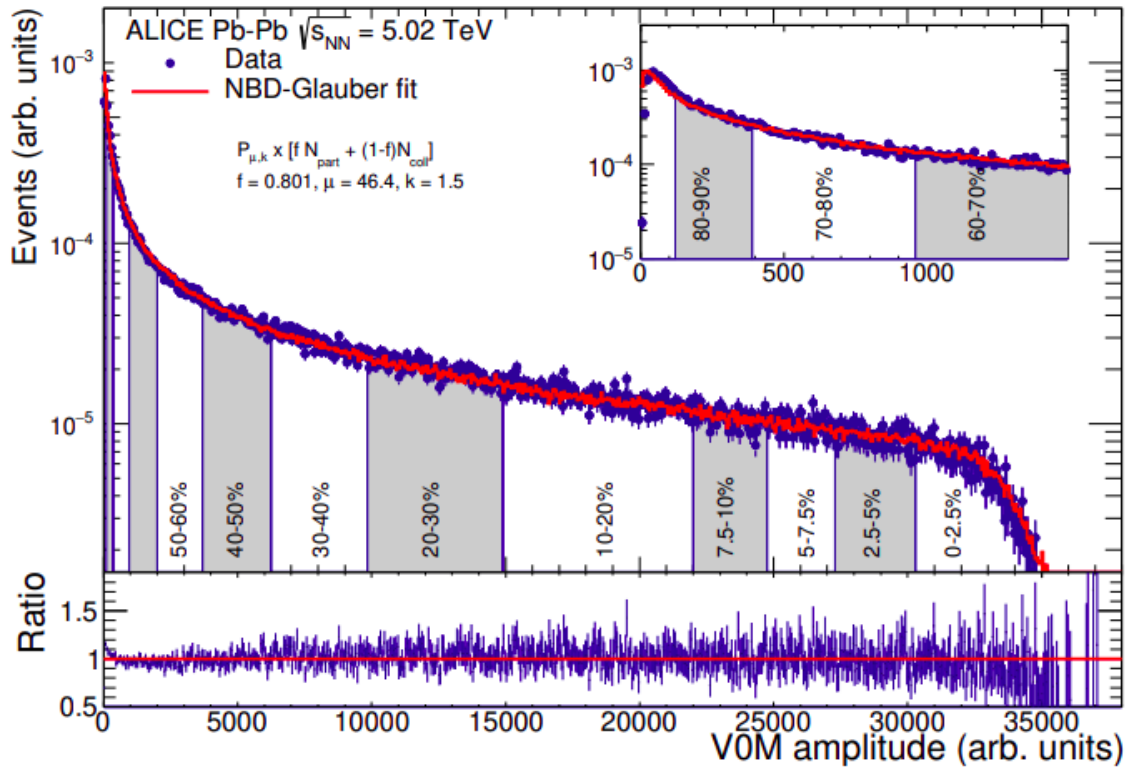


Figure 20: Event distribution as a function of the total V0 signal for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with a corresponding NBD-Glauber fit [140].

The relation between the centrality classes and the collision geometry is modeled through Glauber Monte Carlo simulations. Glauber model simulates the geometry of a heavy-ion collision by treating the two colliding nuclei as an incoherent superposition of binary nucleon-nucleon collisions. The two main inputs of the model are the nuclear charge densities and the energy dependence of the inelastic nucleon-nucleon cross section. The nuclear density follows a two-parameter

Fermi distribution (2pF),

$$\rho(r) = \frac{\rho_0}{1 + \exp(\frac{r-R}{a})}, \quad (10)$$

with the nuclear radius R , the nucleon density in the center of the nucleus ρ_0 and the "skin depth" α [139, 141]. With the Glauber model, the number of binary collisions and the participant multiplicity can be calculated for a given impact parameter. In this model, protons and neutrons are treated the same and are assigned a finite cross-section, $\sigma_{\text{NN}} = 67.6 \pm 0.5$ mb. At high energies, the nucleons are assumed to follow eikonal trajectories, i.e. trajectories without deflections. Following this approximation and the assumptions of the Glauber model, the initial geometry of a heavy-ion collision can be calculated analytically as a function of the nuclear density and nucleon-nucleon inelastic cross section. For example, the number of binary nucleon-nucleon collisions, N_{coll} , as a function of the impact parameter can be expressed as,

$$N_{\text{coll}} = \sigma_{\text{NN}} \int \rho_{\text{coll}}(x, y, b) dx dy = \sigma_{\text{NN}} \int T_A(x - \frac{b}{2}, y) T_B(x + \frac{b}{2}, y) dx dy \quad (11)$$

, where

$$T(x, y) = \int \rho(x, y, z) dx dy dz \quad (12)$$

are the transverse nucleon density functions for each nucleus A and B normalized to the number of nucleons in each nucleus.

Glauber Monte Carlo simulations [139] coupled with the NBD model [140, 142] are used to calculate the event multiplicity. In the ALICE experiment, the signal of the V0 detector is fitted with the distribution predicted from the NBD-Glauber model. The signal is normalised to an anchor point which corresponds to 90% of the total hadronic cross section determined by the NBD-Glauber fit. Events with lower multiplicity than the anchor point are contaminated by electromagnetic background and therefore discarded from the centrality fit. Fig. 20 shows a fit of the V0 amplitude with the NBD-Glauber model for Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

4 ALICE Offline Analysis Framework

This brief chapter is devoted to the software framework (Section: 4.1) and the computing infrastructure (Section: 4.2), both of them essential for the results of this dissertation. Combined with the preceding Ch. 3, they complete the picture of the necessary "tools" which were employed in this work.

4.1 AliRoot and AliPhysics software

The two main software frameworks which are used for the analysis of experimental and simulated data are AliRoot [143] and AliPhysics [144]. Both of them, are ALICE specific libraries based on the more general ROOT [145] software which is widely used in high energy physics research.

ROOT is a software framework for data processing, statistical analysis, efficient storage and data visualisation. It contains a vast collection of C++ libraries as well as a line-by-line interpreter. Furthermore, the ROOT framework allows the transparent use of other programming languages like Python or R.

AliRoot and AliPhysics serve as additional software layers. They include modules for the event and track reconstruction and related selection criteria. The FastJet [146, 147] framework which provides implementations of many jet finding algorithms and tools for advanced jet manipulation is included in AliPhysics. Monte Carlo generators which are commonly used in ALICE analysis are also a part of this framework. All of the code that was employed during this dissertation was developed within the ROOT framework and the primary analysis tasks are part of the AliPhysics library.

4.2 GRID computing framework

A year of operation at the LHC produces several Petabytes of data. In addition, large scale Monte Carlo productions to simulate the detector performance in each data taking period are required to evaluate the detector response and correct the measurements for its effects. This task is undertaken by the GRID [148], an extended computing infrastructure which spans multiple research centers in many countries. The ALICE Offline collaboration has developed an environment called AliEn (ALICE Environment) [149] which facilitates the access to the GRID.

The result of the global reconstruction of real and simulated data is stored in ESD (Event Summary Data) ROOT files which contain physics information as well as quality assurance information for each subdetector. For the reduction of storage and the optimization of computing time usage, many analyses use AOD (Analysis Object Data) ROOT files which are more compact and derived from the ESD files.

The Alien framework provides authentication, virtual file catalogue and job management to every collaboration member. Lastly, the status of the GRID computing centers and the progression of the analysis jobs can be easily visualised through MonALISA (MONitoring Agents using a Large Integrated Services Architecture) [150] an easy-access online web interface. Each collaborator can submit and monitor individual jobs on the GRID but there is also the possibility for a more coordinated analysis on a larger scale through the use of the LEGO train framework [151].

5 ALICE data and Monte Carlo samples

This chapter gives a short description of both the ALICE collected (Sec. 5.1 and 5.2) and simulated data (Sec. 5.3 and 5.4) samples for the pp and the Pb-Pb collision systems. All of these input data is in the form of AOD ROOT files as they were described in Sec. 4.2. On the other hand, Sec. 5.5 describes the simulations produced with the JEWEL model locally for the purposes of model comparison.

5.1 ALICE pp dataset

The work presented in this dissertation analysed the ALICE data which were collected during the Run 2 campaign. The pp collision data samples analysed in this thesis were collected from 2016 up to and including 2018. For these data, the collision energy in the center-of-mass frame is $\sqrt{s} = 13$ TeV and for the purpose of maximizing statistics, a minimum bias trigger was employed. As it will be discussed in the section below, the collision energy of the heavy-ion sample is lower than in the pp collisions. In order to investigate the dependence of the measurement on this parameter, a comparison at the reconstructed level with pp data collected at $\sqrt{s} = 5.02$ TeV in 2017 was carried out. As it will be shown in Ch. 13, the dependence is mild so the analysis proceeded with the higher collision energy sample due to the increased statistical precision.

5.2 ALICE Pb-Pb dataset

For the analysis of Pb-Pb collisions, the ALICE data were also collected in Run 2 during 2018 at $\sqrt{s_{NN}} = 5.02$ TeV. As it was mentioned in Sec. 3.6, due to the finite size of the nuclei, the Pb-Pb collisions can be classified as a function of their impact parameter from central or head-on collisions to peripheral. This analysis focused on the most central events in the centrality percentile of 0 – 10%, since in these cases the evidence of jet quenching is the strongest. This effect follows from the higher temperature of the QGP medium produced in these collisions. In terms of trigger selection, the accepted events satisfied either the minimum bias or the central collision trigger (see Sec. 3.6).

5.3 ALICE PYTHIA productions

In addition to the data reconstruction and analysis, an important role fulfilled by the LHC GRID is the central production of MC simulations. These are used for physics analysis but also to simulate the response of the ALICE detector. The MC event generator used to simulate pp collisions is PYTHIA8 [152]. PYTHIA includes a coherent set of physics models for the evolution from a few-body hard process to a complex multi-particle final state. Specifically, it contains models for initial- and final-state parton showers, matching and merging methods between hard processes and parton showers, multiparton interactions, beam remnants, hadronisation through string fragmentation and particle decays. PYTHIA has many free parameters which have to be tuned in order to provide a good description of the experimental data. These parameters tune the parton cascade, the non-perturbative hadronisation process as well as the description of the underlying event. The PYTHIA8 tune which was used in this thesis is the Monash2013 [153].

Additionally, the transport of the MC produced particles through the detector system is simulated with GEANT3 [154, 155]. GEANT3 is a software package which includes a detailed description of the detector configuration for each run period. Due to this procedure it is possible to

compare the measurement in data with model predictions at the reconstructed or detector level. The correspondence between particle or truth level and detector level information is essential. Due to this relation, through a procedure called unfolding (Sec. 8.6) the collected data can be corrected for the effects of detector response. In this way the comparison of measurements between experiment and theory or between experiments which use different detector setups is possible.

With this goal in mind, the MC simulations which were used in this thesis correspond to the central ALICE PYTHIA8 productions anchored in the detector performance of each data collection period between 2016 and 2018.

5.4 Embedded PYTHIA productions in ALICE Pb-Pb data

As it was outlined in the section above, MC simulations with an appropriate detector response can offer a correspondence between a measurement at the reconstructed and the particle level. In the case of Pb-Pb collisions there is no commonly accepted event generator that can act as the equivalent of PYTHIA8 in pp collisions. There are models which include parton energy loss, such as JEWEL [110, 156] which will be addressed in the next subsection and Ch. 9, or that can describe the hydrodynamic evolution of the QGP medium. However, the accepted practice within the ALICE jet analysis community [157] is to approximate the detector response in a heavy-ion measurement by embedding a PYTHIA8 signal with its corresponding detector level counterpart in an minimum bias Pb-Pb collision event from the ALICE data. By making sure that the detector response is anchored to the appropriate heavy-ion data taking period and through the application of background subtraction techniques (Sec. 8.5) it has been shown that this process can simulate the behavior of real data to a very good extent. Furthermore, it has been found that the detector has a lower tracking efficiency in an environment of high particle density. In order to account for this effect, 2% of the reconstructed PYTHIA8 signal tracks at the detector level are randomly rejected in each event.

In this analysis, a PYTHIA8 production anchored to the detector performance during the Run 2 campaign in 2018 was embedded in events from that dataset. For the purposes of computing efficiency, it is possible to embed different signal events in the same Pb-Pb event (recycling). Since it is unlikely that different PYTHIA jet signals are embedded in the event at the same position, the signal jets probe different medium fluctuations. However this recycle scheme should not be abused in order to avoid a systematic bias in the approximation of the background contribution. In addition, it should be noted here that the current implementation of the embedded PYTHIA8 analysis on the LEGO train system [151] results in a significant computing load. This aspect becomes particularly important in the evaluation of systematic uncertainties for the Pb-Pb measurement since a complete embedding procedure should be repeated for each of the systematic variations.

5.5 JEWEL Monte Carlo sample

In this thesis, MC simulations of the JEWEL quenching model were analysed. This study served as a testing ground for the exact definition of the jet observable, the measurement of which is presented in this dissertation. The JEWEL MC study also reinforced the motivation for the measurement in ALICE data based on the observable's sensitivity to jet quenching effects. These results are presented in Ch. 9.

JEWEL is a MC event generator which simulates the QCD jet evolution in heavy-ion collisions. The interplay between QCD radiation and re-scattering in a medium is treated fully microscopically in a perturbative approach. It is not a full heavy-ion event generator and shares ingredients with

Parameter	pp	AA w/o recoil	AA w recoil
PTMIN [GeV/c]	8	8	8
PTMAX [GeV/c]	1000	1000	1000
ETAMAX	2.5	2.5	2.5
SQRTS [GeV/c]	5020	5020	5020
MASS	1	208	208
KEEPPRECOILS	FALSE	FALSE	TRUE
WRITESCATEN	FALSE	FALSE	TRUE

Table 1: Configuration parameters for JEWEL simulation in the three cases.

Parameter	Value
TAUI [fm]	0.4
TI [GeV/c]	0.44
SIGMANN [fm ²]	7.2
A	208
TC [GeV/c]	0.17
CENTRMIN [%]	0.
CENTRMAX [%]	10.

Table 2: Medium parameters for the JEWEL AA simulations used in these thesis.

PYTHIA6 in terms of matrix element production, initial state parton shower, hadronisation and hadronic decays. The model provides a large variety of configuration options. Particularly for the simulation of heavy-ion collisions, there is an option to propagate the medium recoil particles in the track record. As the products of the initial hard scattering propagate inside the medium and interact with its constituents, the latter are the recoil products of this scattering. Further information on the inclusion of recoil particles in the event track record is presented in Sec. 9.1. The samples analysed in this work correspond to one of the three cases:

1. production in vacuum (pp)
2. production in a nucleus-nucleus collision system without recoils (AA w/o recoil)
3. production in a nucleus-nucleus collision system with recoils (AA w recoil)

The configuration parameters of the simulations used in this thesis are shown in Tab. 1 and 2. Any parameters not listed maintained their default values listed in Ref. [110].

The production in vacuum is identical to a PYTHIA6 simulation and can serve as a reference measurement. The other two options include both medium-induced radiation as well as the parton re-scattering with medium constituents. The decision about including the medium recoil centers before hadronisation in the event record is the distinguishing factor between the two AA modes. This option was initially motivated from computing and storage efficiency reasons since high multiplicity events including recoils can lead to very large output files. The analysis presented in this dissertation was carried out on samples produced locally for all of the three options. A more detailed discussion on the influence of the recoil mechanism is reserved for Sec. 9.1.

Part III

Introducing Jet Energy Flow Fluctuations

6 Jets in Heavy Ion Collisions

This chapter can be seen as an extension of the ideas presented in Ch. 2 to the realm of jet physics. The interactions between the products of the hard scattering and the medium constituents described in Sec. 2.2 lead to the modification of jets as they propagate through the Quark-Gluon Plasma (QGP). The phenomena which describe the medium induced jet modification are referred as *jet quenching*. These effects are addressed in Sec. 6.1. A selective overview of expected jet quenching experimental signatures with an emphasis on the measurement of jet yield suppression is provided in Sec. 6.2 and Sec. 6.2.1, respectively. This chapter concludes in Sec. 6.3 with a list of open questions in the field of jet physics in relativistic nuclear collisions.

6.1 Aspects of jet quenching

Jet quenching refers to the modification of jets in heavy-ion collisions. This is caused by their interaction with the medium of deconfined matter produced during the collision. From the experimental point of view, jets are composite physical objects defined by a jet clustering algorithm (Sec. 1.3). As composite objects, their modification can manifest in multiple aspects.

The most straightforward aspect of quenching is that jets lose energy as they traverse the QGP. This effect arises from the parton energy loss due to the interactions with the medium constituents (Sec. 2.2). Jets probe the entire parton shower and therefore their energy loss is sensitive to all of the parton energy loss mechanisms and their interference. Based on this effect, a clear signature of jet quenching is the suppression of jet yield at a given energy with respect to the number of jets produced in pp collisions [158]. Naturally, the energy in these interactions has to be conserved. Therefore the missing jet energy is either deposited outside the jet cone, or absorbed by the surrounding medium [37, 159]. The understanding of the energy redistribution mechanism is one of the primary goals of jet research in the heavy-ion community.

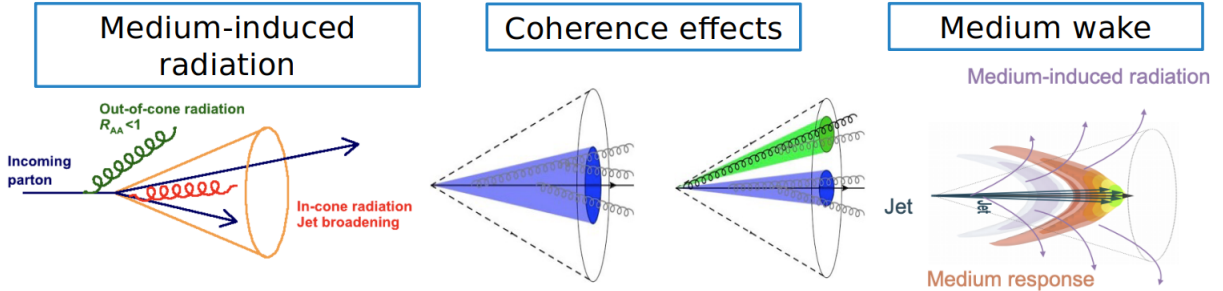


Figure 21: A schematic view of the possible jet quenching effects [64, 160].

The interactions of the jet partons with the medium lead to momentum loss along their trajectory. As a consequence of these interactions, the jets as a whole exhibit energy loss. However, theoretical calculations predict that jet partons can also pick up momentum transverse to their original direction through their scatterings with the medium constituents. This effect would lead to a broader jet parton distribution in the momentum space which is why this expectation is referred to as p_T broadening [37]. The term of jet broadening has been used to describe both the modification of the angular substructure of the jet (intra-jet broadening) as well as the deflection of the jet as a whole due to medium scatterings (inter-jet broadening). This theoretical prediction is present

in many theoretical approaches [108, 161, 162] and has sparked multiple experimental analyses of jet substructure observables [163–168]. Measurements of p_T broadening can determine the values of the transport coefficient $\hat{q}$ of the QGP [162]. Jet broadening has been confirmed experimentally by the CMS measurement of the jet radial profile modification in heavy-ion collisions [169].

Furthermore, jet quenching effects are closely related to the angular structure of the parton cascade. Particularly, parton showers with a wide opening angle will be resolved by the medium as individual incoherent radiation emitters. The lack of coherence among those sources will lead to greater jet energy loss (see Sec. 2.2). Therefore wider jets will be more quenched by their interaction with the medium [170–172]. Consequently, the jet population that comes out of the medium will be on average narrower. In other words, the radial energy density profile of jets will be narrower in heavy-ion compared to pp collisions [37]. Evidence of this feature have already been observed in jet shape measurements [169, 173]. The angular structure of the jet is closely connected to the flavor of the parton that initiated the shower. Gluon-initiated jets include more soft constituents with a broader angular distribution compared to quark-initiated jets. As a result, the fraction of quark-to-gluon initiated jets is an important factor in the interpretation of jet substructure measurements [174].

Finally, the modification of the jet induced by the medium causes an excitation of the latter along the path traversed by the jet. The energy and momentum deposited into the medium by the fast moving partons of the jet can affect the medium temperature and local velocity field. The jet induced medium response consists of the wake front and the diffusion wake. Microscopically, each jet-medium interaction kicks the medium parton into a recoil particle and leaves behind a “particle-hole”. Further transport of the recoil particles forms the wake front, while the diffusion of the “particle-holes” leads to the diffusion wake. The wake front can manifest as a shockwave with a characteristic Mach cone. The Mach cone angle is related to the speed of sound in the medium and can therefore be used to determine this property of the QGP. The medium wake front will lead to an enhanced correlated hadron production in the direction of the jet while the diffusion wake will cause a depletion of soft hadrons in the opposite direction [175–177]. It is possible that some of the soft hadrons produced by the wake will end up in the experimentally defined jet cone. Evidence of this effect has been found in di-jet asymmetry measurements [178] as it will be described in the next section. A nice review of the relation between jet quenching and medium response is presented in Ref. [118].

A schematic depiction of the jet quenching effects and their sources is shown in Fig. 21. Although these aspects of jet quenching are distinct there can be significant overlap between their effects in the interpretation of experimental jet measurements.

6.2 Evidence of jet quenching

The effects of jet quenching manifest as the modification of jet observables in heavy-ion collisions compared to reference measurements in pp collisions. This section describes some of these characteristic signatures either observed or expected based on theoretical calculations. The aim is to provide an introduction to the experimental jet quenching field rather than an exhaustive list of all the jet observables developed through the years.

1. **Di-jet momentum imbalance:** A direct evidence of jet quenching was the observation of momentum imbalance between the reconstructed jets produced in a back-to-back configuration. Based on momentum conservation, the two jets should have balanced momenta.

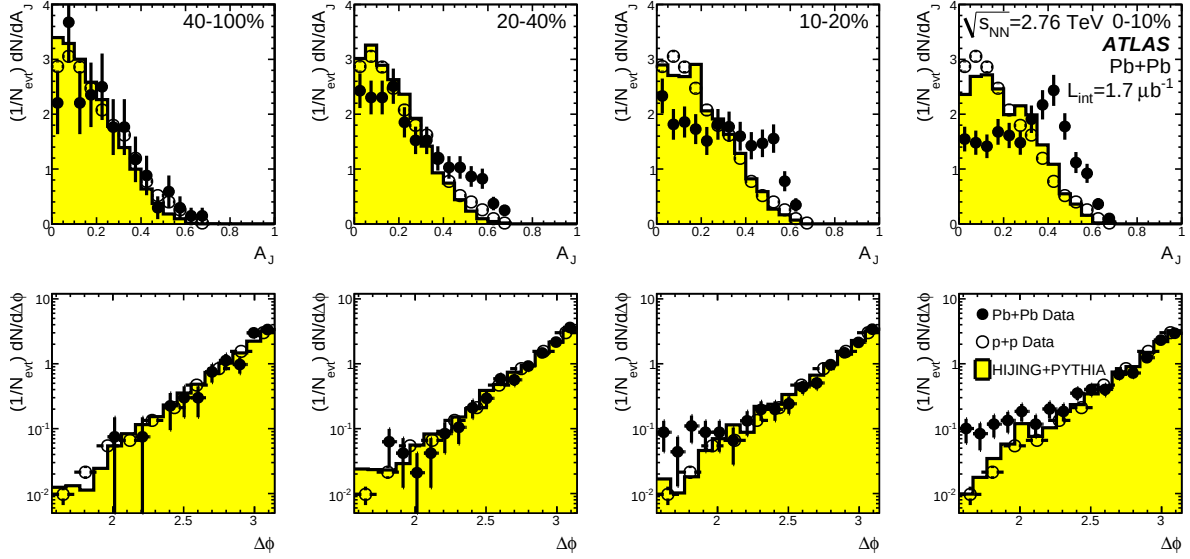


Figure 22: Top row: Comparisons of A_j between pp and Pb-Pb collisions in different centralities. Bottom row: The angular distribution of the jet pairs [179].

Measurements of the momentum imbalance,

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad (13)$$

have been performed in pp and Pb-Pb collisions. However, even in the absence of QGP in pp collisions perfect momentum balance is not observed due to out-of-cone radiation, kinematic and detector effects [159].

Di-jet imbalance measurements have been performed by both the ATLAS [179, 180] (Fig. 22) and CMS [178] experiments and both of them observe a shift towards larger asymmetries in central Pb-Pb collisions. The di-jet asymmetry enhancement in these collisions is consistent with expectations of jet energy loss. Conversely, in peripheral collisions the measurements agree with the reference measurement in pp collisions. It is worth noting that even asymmetric di-jet pairs do not exhibit signs of inter-jet angular broadening since they have similar angular correlations with respect to the leading jet. Furthermore, it was found in the CMS measurement that the momentum imbalance can be restored if soft particles distributed in very large angles ($\Delta R \geq 0.8$) around the jet are taken into account [178]. This observation could indicate the presence of medium wake in the direction of the jet.

Measurements of the di-jet system probe the dependence of jet energy loss on the medium path-length traversed by the jet. Jets created in the center of the QGP traverse a long path inside the medium, which translates to more medium interactions and therefore higher energy loss compared to jets produced near the surface of QGP medium. In a di-jet measurement, comparisons to the leading jet energy, which has experienced less energy loss, lead to a bias towards the jets which have traversed a short path in the medium. Disentangling this surface bias effect from the influence of other jet quenching mechanisms is challenging. Extensive studies of the modification of di-jet pairs in heavy-ion collisions have been recently conducted by the ATLAS collaboration in Ref. [180].

2. Jet substructure measurements: Jet substructure observables aim to study the medium

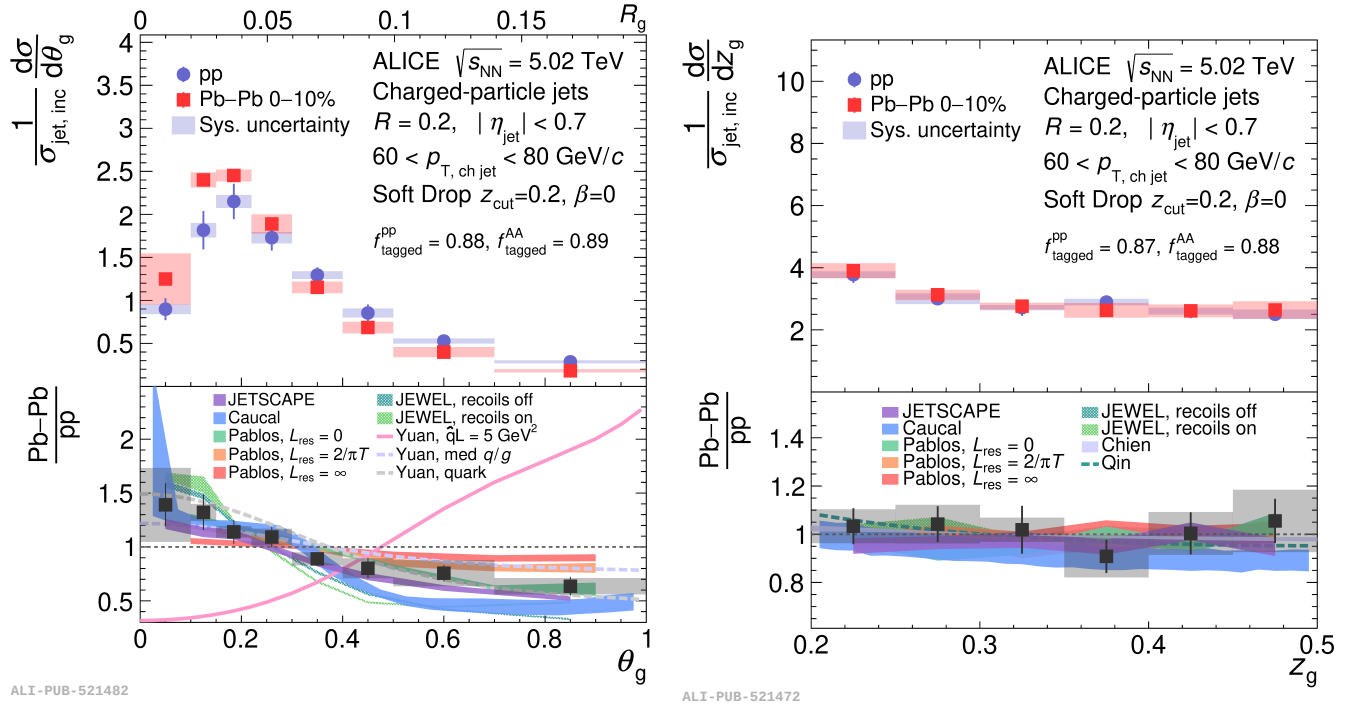
(a) Normalised groomed jet radius $\theta_g = \frac{r_g}{R_{jet}}$.(b) Groomed jet momentum splitting fraction z_g .

Figure 23: ALICE measurements of the groomed jet observables in pp and Pb-Pb collisions are presented and compared with multiple model predictions [163].

induced modification of the jet shower. The evolution of the parton shower from the initial hard scattering to hard and successively softer branch splittings can be analysed through jet substructure measurements. Techniques have been developed where the reconstructed jet is re-clustered with the aim of isolating particular subjets or splittings in the parton shower history. These jet splittings populate the Lund plane which represents the radiation pattern in terms of relative angular and momentum coordinates [181, 182]. Furthermore, grooming strategies have been introduced which iteratively discard the soft components of the parton shower. The goal of the grooming procedure is to define observables which are insensitive to soft radiation and therefore can be calculated perturbatively. With these techniques it can be established whether the medium modification takes place during the hard scattering stage or during the later fragmentation phase. A popular grooming algorithm is SoftDrop [183], which examines the de-clustered jet splittings and discards the sub-leading subjets until the branches of the splitting satisfy the grooming condition,

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \geq z_{cut} \theta^\beta,$$

where θ represents the angular separation of the branches and the parameters z_{cut} and β define how strict the grooming procedure is. Based on this algorithm, two groomed jet observables have been defined: the momentum splitting fraction $z_g = \frac{p_{T, sublead}}{p_{T, sublead} + p_{T, lead}}$ and the radius $r_g = \sqrt{\Delta\eta_{1,2}^2 + \Delta\phi_{1,2}^2}$.

Both distributions of these observables have been measured by the ALICE experiment [163],

shown in Fig. 23b and Fig. 23a respectively. It was found that jets have a narrower substructure in Pb-Pb collisions compared to pp collisions. Separately, the distribution of momentum splitting fractions in heavy-ion collisions is consistent with the corresponding measurement in vacuum. In addition, ATLAS measurements of the jet yield suppression (Sec. 6.2.1) as a function of the groomed jet radius have shown that jets with large r_g are more suppressed [184]. This conclusion is in agreement with expectations based on radiation coherence effects.

Investigations of the jet splittings in the history of a parton shower can also be used to find evidence of point-like parton scattering off the medium constituents or Molière scattering [185]. Such effects would lead to an excess of hard $k_{T,g} = p_{T,sublead}r_g$ splittings in heavy-ion collisions. The signature of large angle jet deflection due to the scattering of the hard parton with the medium constituents is much sought-after by theorists since it would constitute explicit evidence of the QGP's point-like degrees of freedom. Unfortunately experimental confirmation is still missing. First measurements of the hardest k_T splitting performed by the ALICE collaboration [186] exhibit a better agreement between data and models which do not include the Molière scattering effect (Fig. 24).

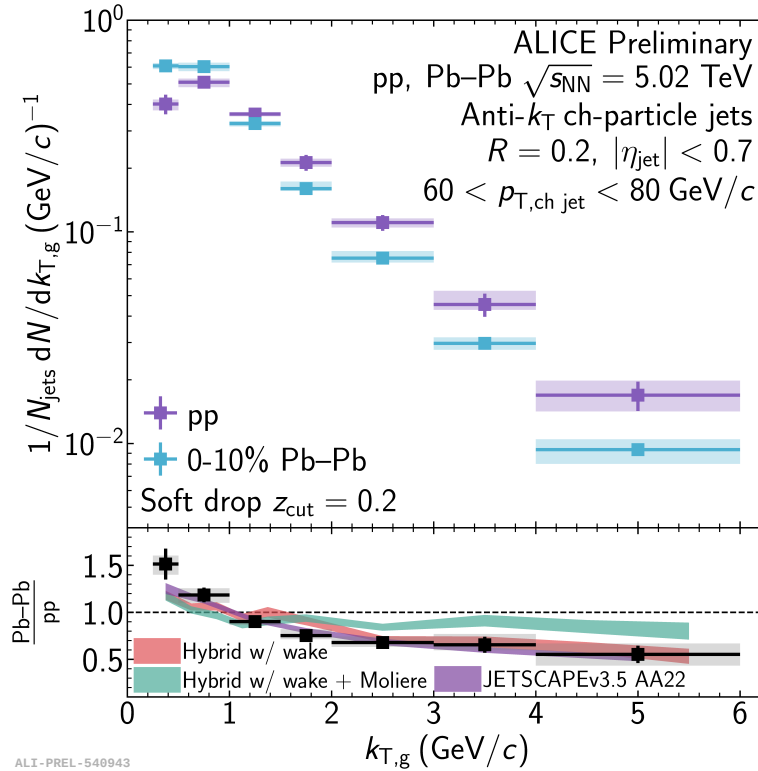


Figure 24: ALICE measurement of hardest k_T splitting in Pb-Pb collisions [186].

3. **Jet quenching flavor dependence:** The dependence of jet quenching effects on the nature of the initiating parton (quark or gluon) is colloquially referred to as flavor dependence. In addition, this term can also refer to the dependence on the different quark flavors and their relative mass difference. Theoretical calculations predict that quarks and gluons should be characterised by distinct radiation patterns. Particularly, gluon showers are characterised by a broader and softer fragmentation pattern while quark-initiated showers tend to be narrower. For inclusive jets it is experimentally impossible to distinguish between gluon- and quark-initiated jets in hadronic collisions. However, correlation measurements of jets produced

coupled to a neutral boson (γ -jet or Z boson-jet pairs) provide a strong handle on the flavor of the initiating parton, since they will primarily be quark-initiated jets. These measurements are particularly useful when compared to their counterpart measurements performed for an inclusive sample of jets. An additional advantage of these correlation studies is that the trigger neutral boson does not interact with the medium and therefore reflects the energy of the initiating parton. This attribute is particularly important for the proper evaluation of jet energy loss and the direct comparison with theoretical predictions. Measurements of the nuclear modification factor (see Sec.6.2.1) by the ATLAS collaboration have shown that γ -jets which correspond to a large fraction of quark-initiated jets are less suppressed compared to the inclusive measurement which tends to be dominated by gluon-initiated jets [187]. In addition, jet broadening in the QGP has been directly observed in the CMS measurement of jet shapes for *gamma*-jet samples [188].

The flavor dependence of jet quenching can also be studied for jets which are tagged with the presence of a heavy-flavor quark. It is expected that the massive quarks result in a suppression of radiation in small angles. This phenomenon is referred to as the dead-cone effect and it is expected to be more evident for heavy quarks like charm and bottom. The dead-cone effect is a fundamental QCD phenomenon and it has been recently observed in a measurement by the ALICE collaboration [189]. Fig.25 shows the ratio of splitting angle probabilities for jets tagged with a charm meson (D^0) over inclusive jets. A clear suppression of the ratio is observed in the pink shaded regions, where the dead-cone effect is expected to play a role. This measurement has been done for pp collisions for the charm meson and has sparked the interest for follow-up studies in a heavy-ion environment as well as for jets tagged with the heavier bottom quark.

The effect of the quark mass dependence has been investigated in measurements of yield suppression [190] as well as jet shape modification [191] by the ATLAS and CMS collaboration respectively. The field of heavy-flavored tagged jet studies is broad and very interesting, a recent review of the theoretical progress on the topic is provided in Ref. [192].

6.2.1 Nuclear modification factor

Medium induced parton energy loss will inevitably lead to reduced particle yield in heavy-ion collisions at a given particle energy compared to pp measurements. This yield suppression can be characterized with the nuclear modification factor R_{AA} . It is defined as the ratio of the inclusive yield per rapidity unit in nuclear collisions over the corresponding cross section in pp collisions scaled by the nuclear overlap function $\langle T_{AA} \rangle$,

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2 N_{AA}/dp_T dy}{d^2 \sigma_{pp}/dp_T dy}. \quad (14)$$

Deviation of the measurement from unity signifies a suppression ($R_{AA} < 1$) or enhancement ($R_{AA} > 1$) of the yield in nuclear collisions.

Measurements of R_{AA} have been performed by many experiments both at LHC and RHIC for inclusive charged particles as well as for identified hadrons [193, 194]. The investigations of this observable span an extended range in parameters such as: collision energy, system size, particle transverse momentum. Furthermore, the R_{AA} has also been measured for composite objects such as jets [195], as function of the jet transverse momentum for a variety of jet cone sizes. An extensive review of all these measurements and their interpretation can be found in Ref. [53, 54, 159].

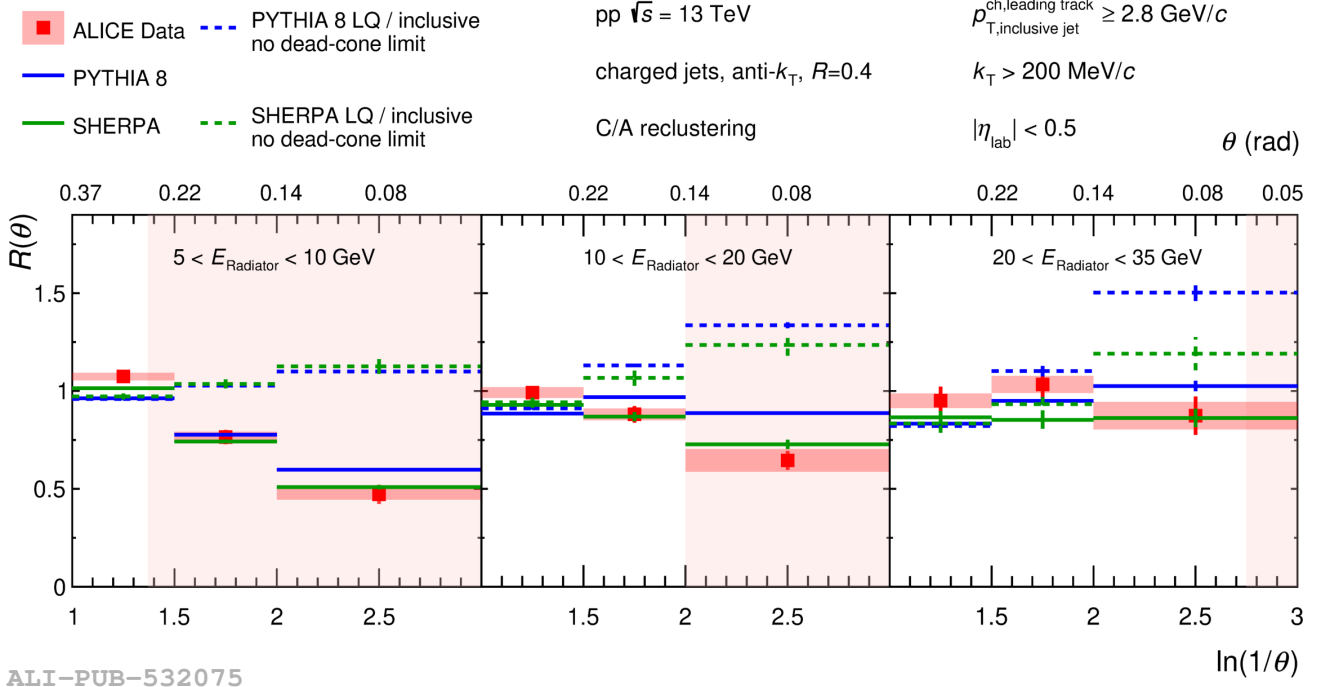
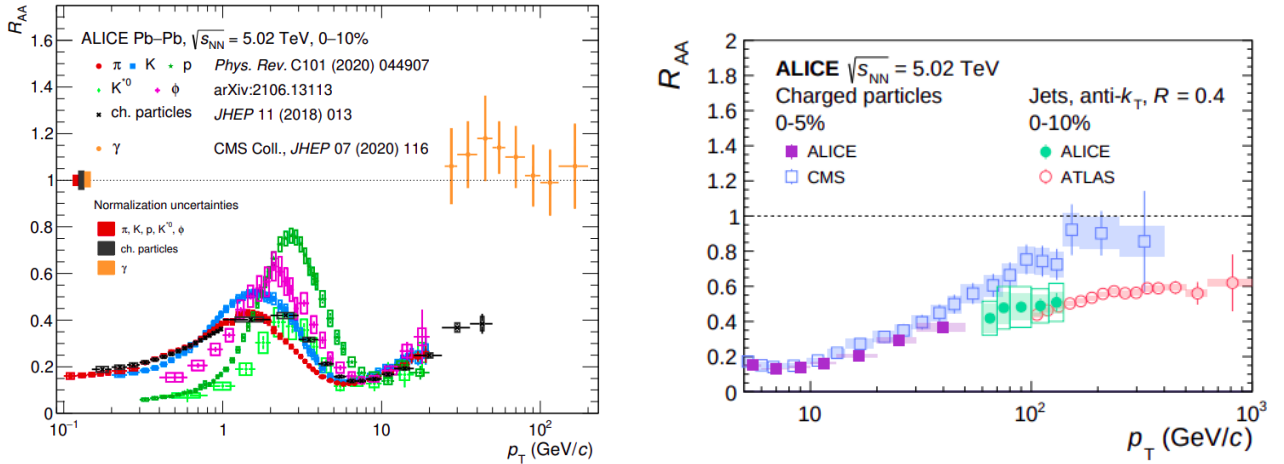


Figure 25: Ratios of splitting angle probability distributions. The ratios of the splitting-angle probability distributions for D^0 -tagged jets to inclusive jets, $R(\theta)$ measured in pp collisions at $\sqrt{s} = 13$ TeV in three regimes of charm-quark energy are shown. The data are compared with models with and without the dead-cone effect. The pink shaded areas correspond to the angles within which emissions are suppressed by the dead-cone effect, assuming a charm-quark mass of 1.275 GeV/c [189].

Fig. 26a shows the measurement of R_{AA} for many hadron species as a function of the transverse momentum. Yield suppression is observed for all of the hadron species with a peak at intermediate p_T . This peak exhibits the mass ordering of the different species which is related to the collective radial flow of the hadrons in heavy-ion collisions. At larger transverse momentum the different hadron species approach a similar level of suppression which suggests that energy loss is an effect that takes place at the parton rather than the hadron level [53]. After this peak, there is a minimum at $p_T \approx 6$ GeV/c, and then the R_{AA} increases. The increase suggests that energy loss as observed by measuring high- p_T hadrons is not proportional to the parent parton energy, but closer to constant [196]. As a control probe, the R_{AA} of photons measured by CMS is also shown in the same plot. Since photons do not carry color charge they remain unmodified by the medium and therefore do not exhibit a yield suppression. This effect has also been confirmed for neutral Z bosons.

The corresponding measurements of the jet nuclear modification factors are shown in Fig. 26b. In the momentum region where the measurements overlap, hadrons demonstrate a smaller yield suppression compared to inclusive jets. It is worth noting that high energy hadrons and jets probe slightly different aspects of jet quenching. While jets are sensitive to the modification of the shower, high- p_T hadrons are sensitive to the energy loss experienced by the hardest branch of the jet shower. The p_T spectrum of the inclusive jets is harder compared to the high energy hadrons but also, due to its effective resolution, a reconstructed jet will capture a fraction of medium induced radiation. As a result, the jet yield should be less suppressed and therefore have a larger

R_{AA} . In fact the opposite is observed. However this comparison holds the caveat that the jets and hadrons at any given p_T were initiated by partons with different energies. For a meaningful comparison the inclusive hadron population must be mapped to that of jets, taking into account the bias imposed by selecting high- p_T hadrons. Based on model calculations, high- p_T hadrons have their origin in narrow hard fragmenting jets which are expected to be less quenched after their interaction with the medium [170–172]. The expected larger suppression of wide showers leads to an experimental selection bias towards narrow jets. At a given energy, wider jets will lose more energy compared to their narrower counterparts and therefore will be measured as jets with lower p_T . As a result, the high energy jets that "survive" the medium interaction represent a narrow shower population. Since such an effect is not present in pp collisions, inclusive measurements like the nuclear modification factor have to also take into account the experimental selection bias against wide jets. As it was mentioned earlier, a decrease of R_{AA} as function of the groomed jet radius r_g has been observed in recent ATLAS measurements [184]. Disentanglement of the different experimental biases and the effects of competing energy loss mechanisms is especially difficult and requires a systematic study of jet observables differential in the resolution parameter R .



(a) Measurements of the nuclear modification factor for pions, kaons, protons, phi mesons and isolated for charged particles and jets in central Pb-Pb collisions. (b) Measurement of the nuclear modification factor for pions, kaons, protons, phi mesons and isolated for charged particles and jets in central Pb-Pb collisions.

Figure 26: Measurements of R_{AA} for identified hadron species (left), as well as inclusive measurements for charged particles and jets (right) [53].

A natural follow-up in the discussion of jet energy loss is to investigate the re-distribution of this energy. It is expected that this energy is emitted at large angles outside the jet cone. To investigate this in more detail, studies of the dependence of the nuclear modification on the jet radius have been performed [197, 198]. The energy redistribution mechanisms, investigated by the studies of jet radius dependence of R_{AA} , is also the physics goal of the observable and corresponding measurement that is presented in this thesis. A detailed discussion on this topic is presented in Ch. 7.

6.3 Open questions in jet quenching research

This section features a few open question in the study of jet quenching which are vigorously investigated by the scientific community. This is not a detailed and comprehensive collection of topics and both the content as well as the ordering express the author's subjective opinion. With those caveats, some of the big questions in the field of jet research in high energy nuclear physics are:

1. **What is the dominant jet energy loss mechanism and how is the missing energy re-distributed?** The suppression of the jet yield in heavy-ion collisions at a given energy is a clear signature of jet quenching. However, its inclusive nature makes it difficult to disentangle the contributing processes and investigate their relevant dominance. The missing energy is either re-distributed outside the jet cone by large angle gluon emissions or absorbed by the surrounding medium and subsequently thermalized. Investigations of the jet energy re-distribution contribute to the understanding of parton interactions and shed light on the dominance of competing energy loss mechanisms. The search of this missing energy can be elucidated by studying the dependence of jet observables on the jet cone radius. Contributing to an answer of this question is one of the primary aims of the research presented in this dissertation.
2. **What is the nature of the scattering centers inside the medium?** The medium of deconfined matter produced in heavy-ion collisions behaves as a strongly coupled liquid. However, its parton constituents are expected to be asymptotically free and weakly coupled. The reconciliation of these two aspects is challenging. If a hard parton traversing the medium interacts weakly with asymptotically free scattering centers (either quarks and gluons or quasiparticles), then it should be possible to observe large angle Molière scatterings [37, 185]. These effects would translate into deflection of the jets which could be observed in studies of the acoplanarity in di-jet systems or hard kinks in the parton shower [199, 200]. Such predictions are present in the majority of theoretical models but so far experimental confirmation remains elusive.
3. **What are the characteristics of the jet induced medium response and how does it affect jet observable measurements?** The medium of deconfined matter produced in heavy-ion collisions is modified by the deposition of energy and momentum by the jets along their path. The absorbed energy modifies the local velocity field creating a wake front in the direction of the jet. Theoretical models predict that the wake front should exhibit a shockwave structure with a characteristic Mach-cone [175, 176]. Although there has been evidence of this medium wake existence, disentanglement of the medium response from medium induced parton radiation has proven challenging. In addition, a diffusion wake is predicted to cause depletion of the soft hadron yield in the direction opposite to the jet. Conversely an enhancement in yield of Z-hadron correlation measurements has been recently observed [201]. The nature of the medium response and its contribution to the observed jet quenching signatures is the topic of lively debate between theoretical and experimental physicists in the heavy-ion community.
4. **Is a medium of deconfined matter produced in collisions of small systems?** The study of small collision systems such as p-Pb collisions or high multiplicity pp collisions is a very active and interesting field. Signatures of collective behavior that could be explained by the presence of a deconfined medium have been observed in those collisions [202–204].

However, no sign of jet quenching has been found in small collision systems [205]. Collective behavior originates from parton interactions which lead to an expected energy loss for hard probes. It is unclear how the observed collectivity effects in soft particles can be reconciled with the absence of medium modification for hard probes. It is possible that those observations in small systems are not driven by the presence of a medium which behaves hydrodynamically. Regardless of the explanation, progress in those investigations will impact the current understanding of the behavior of the medium in larger systems.

7 Definition of jet energy flow fluctuations

The preceding chapters provide a general introduction to the field of jets in high energy physics as well as a brief description of the ALICE experimental apparatus and its software toolkit. Building on that foundation, this chapter introduces the titular topic of this dissertation which is the measurement of a new jet observable in heavy-ion collisions. Starting from the motivating factors in Sec. 7.1, a key aspect of the analysis is described in Sec. 7.2, before the formal definition of the observable in Sec. 7.3. Furthermore, the relation of this new measurement to previous heavy-ion measurements which probe similar aspects of jet quenching is described in Sec. 7.4.

7.1 Motivation

The goal of this research is to investigate the jet energy redistribution due to its interactions with the QGP (Sec. 6.1). Particularly, the systematic study of jet quenching with respect to the resolution parameter R_{jet} can illuminate the interplay between two competing physics mechanisms. On the one hand, a parton shower with a wide opening angle would be resolved by the medium as multiple incoherent radiation sources. As a result, jets in which the energy flow is spread out in a larger jet cone will exhibit higher jet energy loss. This effect will manifest in a larger suppression of the their yield as a function of jet energy. On the contrary, the medium induced radiation from a parton shower is expected to be distributed to wide angles with respect to the core of the shower. In this case, a larger jet cone would lead to the recapture of this radiation and therefore a smaller suppression (increase of the relative yield) at large radii. The competition of these two mechanisms should have a clear effect on the dependence of the nuclear modification factor R_{AA} on the jet resolution parameter. Specifically, a ratio of the R_{AA} over the R_{AA} for medium-sized jets (e.g $R_{\text{jet}} = 0.2$) could disentangle these two scenarios since each of the mechanisms would lead to opposing trends as a function of R_{jet} . A sketch of these two scenarios can be seen in Fig. 27.

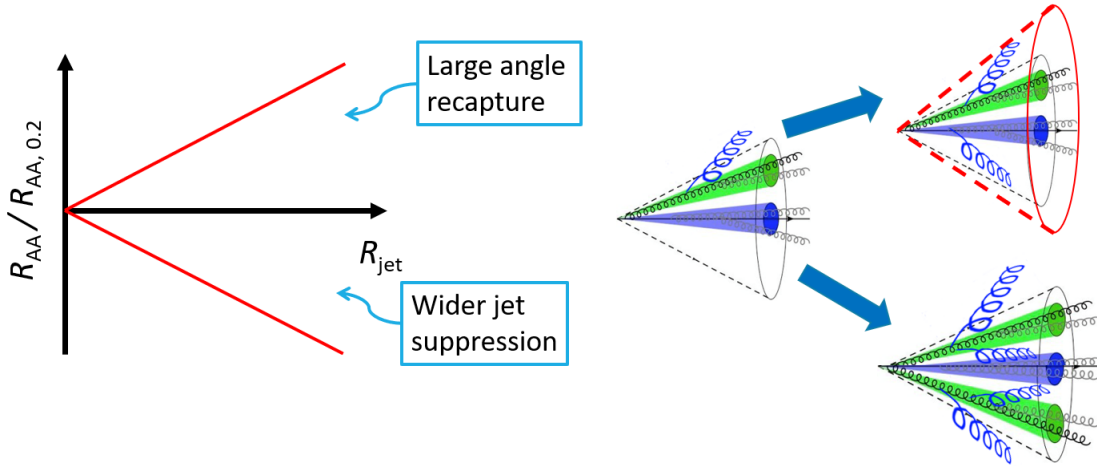


Figure 27: Sketch of the relation between the $R_{AA}/R_{AA,R=0.2}$ measurement and the competing mechanisms.

Measurements by both CMS (Fig. 28) [198] and ALICE (Fig. 29) [197] have investigated the dependence of the nuclear modification factor ratio on the jet size. The ALICE measurement [197] shows a hint of R -dependence at low jet momenta for wide jets. The CMS measurement [198] does not exhibit signs of an R -dependence, although the examined jets have much higher momenta than

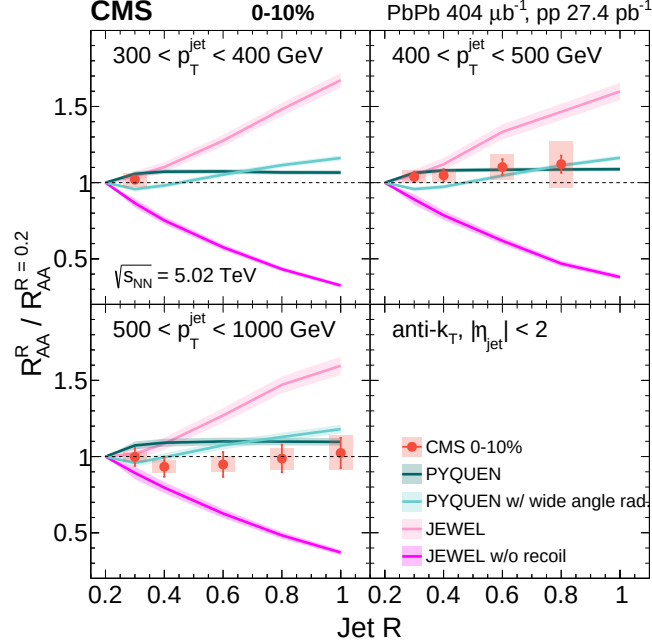


Figure 28: Measurement of $R_{AA}/R_{AA,R=0.2}$ by the CMS collaboration as a function of jet radius. Comparisons of the experimental data with jet quenching models are also provided [198].

in the ALICE result. A p_T -dependence of the quenching effects may constitute the two results compatible with each other. On the contrary, these observations are in disagreement with an earlier ATLAS measurement of the radius dependence of R_{CP} [206]. R_{CP} is an observable similar to the nuclear modification factor, but refers to the ratio of jet yields in central over peripheral heavy-ion collisions instead of comparison to a pp measurement. The ATLAS result demonstrates a significant increase of R_{CP} as a function of R_{jet} especially at lower momenta. It should be noted that the differences in the jet populations considered in the ATLAS and ALICE measurement may contribute to this disagreement. The tension between these measurements has sparked a lot of discussion in the scientific community, which highlights the research interest in the physics probed by these studies. Furthermore, neither the large angle recapture or wider jet quenching mechanism shows a clear dominance. This hints that the two mechanisms are comparable in strength and their individual dominance may change on an event-by-event basis.

7.2 Jet matching

Jet energy loss as a function of the jet resolution parameter can be systematically studied by reconstructing a given parton shower into multiple jets of gradually increasing jet cone radii. A key ingredient of such an analysis would be the sufficient overlap between the larger and smaller jets in the $\eta - \phi$ plane. For the remainder of the dissertation, this requirement is achieved with a procedure called *jet matching* and two plausible cases of matched jets can be seen in Fig. 30. The condition of sufficient overlap between the narrower and wider jets is referred to as geometrical matching criterion. The matching proceeds as follows:

1. For every jet of radius R_{jet} , we calculate the distance of the $R'_{jet} = R_{jet} + dR_{step}$ jets within a maximum range of $\Delta R_{match} = 0.2$.

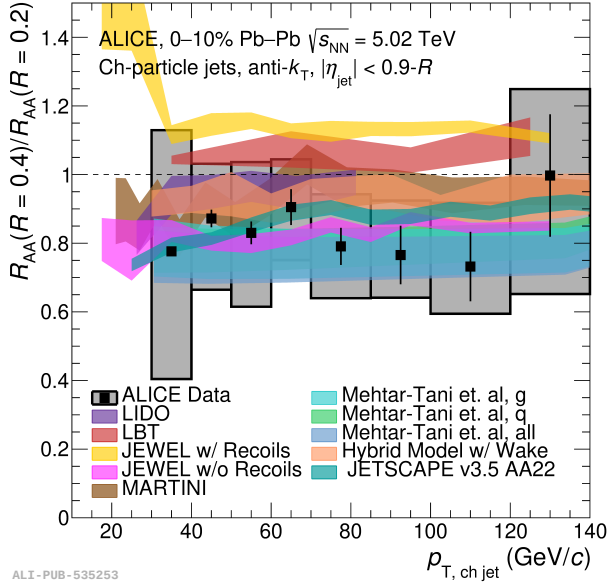
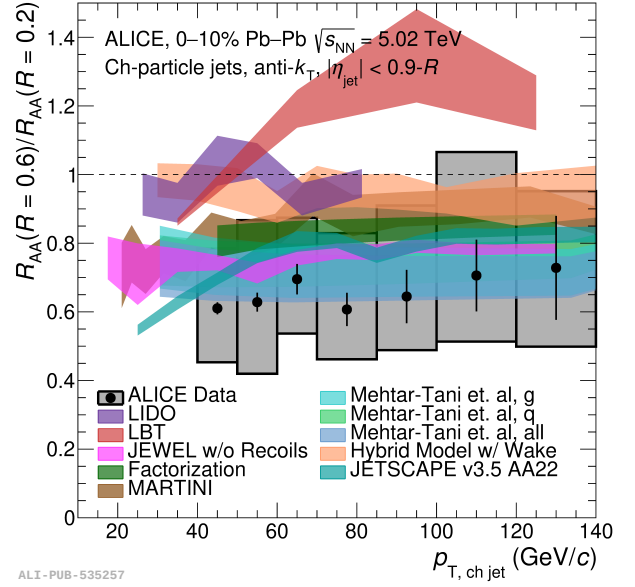

 (a) $R_{AA,R=0.4}/R_{AA,R=0.2}$

 (b) $R_{AA,R=0.6}/R_{AA,R=0.2}$

Figure 29: In the ALICE measurement of $R_{AA}/R_{AA,R=0.2}$ [197] the ratio shows a mild dependence on R_{jet} . A comparison with a variety of model is also depicted.

2. The wider jet which is the closest to the narrow jet is flagged as a potential match.
3. For every R'_{jet} jet, we calculate the distance of the nearby R_{jet} jets within $\Delta R_{match} = 0.2$ and flag the closest narrow jet as match candidate.
4. If the flagged candidates found in the two previous steps are the same (bijective matching), then they constitute a matched jet pair.

The jet pairs identified with the matching procedure serve as the basic object for the calculation of the observable that is defined in Sec. 7.3. In the analysis of MC simulations, a correspondence between jets of a given jet radius clustered at truth level and at detector level is established following the same criteria as the jet matching procedure. In this thesis this procedure is referred to as *jet tagging* to distinguish it from the matching between narrow and wide jets.

As it was mentioned in Ch. 3, each of the ALICE sub-detector systems has a certain coverage in the pseudorapidity range. In most jet analyses to avoid partially reconstructed jets, a fiducial cut is introduced, which corresponds to the acceptance limits of the employed sub-detector reduced by the radius of the jet. This analysis considered a wide range of jet radii and the geometrical matching between the jets was essential. Therefore a fiducial cut based on the η acceptance of the TPC sub-detector and the radius of the largest examined R_{jet} was applied. While this criterion is rather strict for the population of the narrow jets it provides a simple and uniform selection on the analysed parton shower.

7.3 Observable definition

This section introduces a new infrared and collinear safe observable which probes the event-by-event fluctuations of the energy flow between jets. For each matched jet pair, as it was defined in

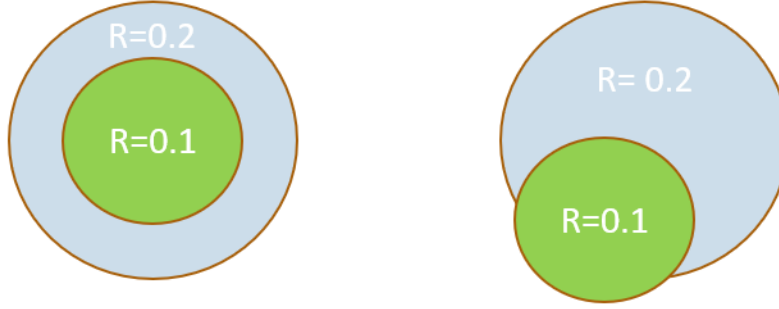


Figure 30: Sketch of the matching requirement between jets of different resolution parameter R . On the left, a case where the jet axes are completely aligned and on the right a more general case where there is significant overlap between the jets but the axes themselves are not aligned.

the previous section, the jet energy flow corresponds to the difference in their transverse momentum p_T between the wide R'_{jet} and narrow jet R_{jet} :

$$\Delta p_T = p_{T,R'} - p_{T,R} \quad (15)$$

The sequential calculation of energy flow between jet populations of increasing jet radius approximates a radial cone expansion around a given parton shower. A comparison of a baseline measurement of this observable in vacuum with its counterpart in a heavy-ion environment can gauge the relative strengths of the large angle recapture hypothesis and the wider jet quenching scenario outlined in Sec. 7.1.

7.4 Relation to other jet measurements

The jet energy flow fluctuation is a new observable which shares some similarities in its definition as well as its physics goals with previous jet substructure measurements. In this section a brief discussion of the relation to some previous measurements is provided while a more in-depth discussion is reserved for Sec. 13.2. In this context, the measurements with the most shared elements are the double ratio of jet nuclear modification factor [197, 198], the jet shape profile [169, 173] and the subjet momentum fraction [166].

By its definition the jet nuclear modification factor probes the modification of jet production in a heavy-ion environment with respect to pp collisions. Studying the dependence of the R_{AA} as function of the jet resolution parameter probes the modification of the jet angular structure. It can also reveal the redistribution of the lost jet energy. The radius dependence of R_{AA} can be probed by the measurement of the double ratio of the nuclear modification factor, $R_{AA,R_{jet}}/R_{AA,R=0.2}$. The numerator corresponds to the nuclear modification factor as a function of jet radius and the denominator is the R_{AA} for a specific jet resolution parameter, *e.g.* $R_{jet} = 0.2$. This quantity can track the flow of energy as the jet cone expands around a parton shower. The measurement described in this dissertation complements this approach and its interpretation connects to the two competing mechanisms described in Sec. 7.1 as it can be seen in Fig. 31. Particularly, if medium-induced radiation deposited at large angles is recaptured, the R_{AA} would increase as R_{jet} grows. This effect would manifest as an increase of the mean energy flow in Pb-Pb compared to pp collisions for wide jets. On the contrary, if wide jets probe wider showers where suppression is

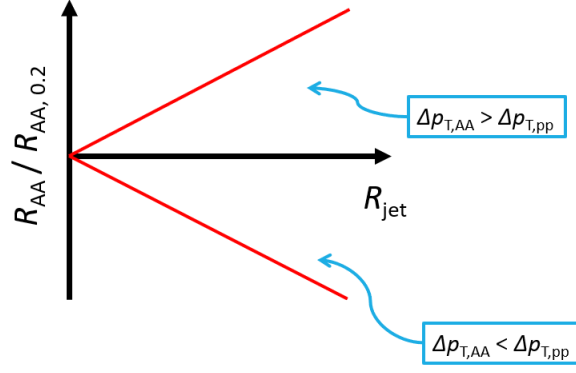


Figure 31: Sketch of the relation between the energy flow fluctuation measurement and the $R_{AA}/R_{AA,R=0.2}$ measurement.

stronger and therefore R_{AA} is smaller, the measured energy gain in pp collisions would be larger compared to the heavy-ion measurement.

The systematic exploration of the energy loss dependence on the angular structure of the shower is also the main overlap between the measurement of jet energy flow fluctuations presented in this work and the observables of jet shape [169, 173] and subjet momentum fraction z_r [166]. The jet shape observable measures the energy density profile around the jet axis at specific radial annuli. In that regard, the energy density at a distance r from the jet axis, $\rho(r)$ is closely related to the mean energy flow $\langle \Delta p_T \rangle$ of that radial pair. This connection is more direct in the case of complete alignment of the two jet axis (Fig. 30 left).

The subjet momentum fraction z_r has similar angular definition as the energy flow measurement. The observable is calculated by re-clustering the constituents of jet with radius R into subjets of a smaller radius $r < R$. The ratio of the subjet's momentum over the jet momentum corresponds to z_r . This observable has been measured inclusively for all the subjets or strictly for the hardest subjet of the jet. The similarities with the energy flow observable are evident with the distinction that matching of the considered (sub-)jet pairs is implicit.

But there are also some differentiating factors between those observables. The study of the Δp_T distribution can give an insight about the event-by-event fluctuations of energy flow within the jets which are not accessible by observables that average over a jet sample such as jet shape. Furthermore, as it will be shown in later chapters, the exponential-like shape of the distribution with a long tail extending up to large Δp_T explores a broad kinematic range. On the contrary, in the subjet fragmentation the subjets are clustered from the constituents of the larger jet and therefore only correspond to cases where $\Delta p_T = 0$.

8 Analysis Strategy

In this chapter, the steps that were followed during the analysis of this dissertation are outlined. An overview of all the steps is provided in Sec. 8.1, serving as a guide to the chapter. The track and event selection criteria for the analysis of experimental and simulated data are presented in Sec. 8.2 and 8.3 respectively. The definition of the analysed jet population and the applied selections are described in Sec. 8.4. For the case of heavy-ion collisions, the treatment of background contributions from the underlying event is addressed in Sec. 8.5. Sec. 8.6 presents the corrections for detector effects through unfolding, and the sources of systematic uncertainties that were considered in this dissertation are outlined in Sec. 8.7.

8.1 Strategy outline

The definition of the observable and the research goals motivating this study were already presented in Ch. 7. This section describes the steps which were followed in the analysis of both experimental ALICE data as well as Monte Carlo simulations in order to achieve those goals.

The first step in the analysis is the definition of the input data. This definition translates to a list of selection criteria that have to be satisfied by the selected events (Sec. 8.2), the reconstructed tracks in these events (Sec. 8.3) and the jets clustered from the accepted tracks (Sec. 8.4). For the analysis of Pb-Pb collisions, the underlying event has a large background contribution to the measurement. This contribution has to be subtracted by the appropriate corrections in the kinematic qualities of the analysed jet population (Sec. 8.5). The next step in the procedure, both for pp and Pb-Pb collisions, is the calculation of the jet energy flow observation with the prerequisite jet matching procedure which was described in Sec. 7.2. At this stage, the first jet energy flow measurement becomes available. In the case of MC simulations, this translates to energy flow distributions at the reconstructed (detector) as well as the particle (truth) level.

The experimental data distributions have to be corrected for the effect of the detector response. This correction is applied through a procedure called unfolding. In the case of heavy-ion analysis, the unfolding process also corrects the measured distributions for the effects of background fluctuations. A key ingredient in the unfolding is the response matrix which encodes the correspondence between the detector and truth level distributions. In order to construct this response matrix an additional geometrical matching has been applied between the jets at the particle and reconstructed level for each investigated jet radius (*jet tagging*). More details of the unfolding procedure and the metrics that are used for its validation are provided in Sec. 8.6.

Following the successful unfolding of the measurements, the last requirement prior to the comparison with other experimental measurements, model predictions or theoretical calculations is the evaluation of the systematic uncertainties. These uncertainties encapsulate our limited knowledge about the assumptions and selections that were employed during the analysis process. The systematic uncertainties together with the statistical uncertainty of the measured sample are necessary in order to evaluate the significance of the result and its levels of agreement with theoretical predictions. More information about this aspect of the analysis are provided in Sec. 8.7.

8.2 Event selection

Event selections corresponds to the online trigger selection and a subsequent offline selection which validates the previous trigger criteria and discards any remaining background events from beam-gas and electromagnetic interactions. For the analysis of pp collisions, the minimum-bias

trigger was applied which corresponds to a coincidence of signals in the V0A and V0C stations (see Sec. 3.6). In the case of Pb-Pb collisions, the minimum-bias trigger was combined with an online trigger selection for the 10% most central events. The event activity is higher in central collisions where the produced medium has higher temperature and density. Therefore the jet quenching effects are stronger in these cases. Further details on the trigger selection based on centrality are described in Sec. 3.6 and 5.2. An additional event selection refers to the position of the primary vertex of the interaction along the direction (z -direction) of the beam. The selected events have a requirement that the reconstructed primary vertex is within 10 cm from the center of detector ($z_{\text{vertex}} \leq 10$).

8.3 Track selection

For the accepted events, a selection on the reconstructed tracks is applied. This selection is based on kinematic criteria and the quality of the track reconstruction. In this thesis, the used tracks are classified as *hybrid tracks*. The introduction of hybrid tracks is related to the fact that in many data taking periods, the SPD layers of the ITS detector were switched off. This lead to inefficient regions in the global track reconstruction. Hybrid tracks aim to provide a uniform distribution in the $\eta - \phi$ plane and include three types of tracks:

- Global tracks with measurements on the SPD layers and a good fit in the full ITS.
- Global tracks without measurements on the SPD layers but with a good fit in the remaining four ITS layers. This type of tracks is constrained to the primary vertex.
- Global tracks with a poor fit in the measured ITS layers. This type of tracks is also constrained to the primary vertex.

From the three categories the first type of tracks gives the best momentum resolution. For the determinations of the primary vertex which constrains the last two categories, only tracks with measurements in the SPD layers are considered. The selection criteria on these hybrid tracks include requirements on: the minimum number of TPC clusters assigned to the track, the maximum distance of the track from the primary vertex in the $(x-y)$ plane as well as in the beam (z -)direction and the quality of the track fit (both for TPC-only tracks and the agreement between global and TPC-only tracks).

8.4 Jet analysis selections

The selections on the kinematic variables of the analysed jet population and their constituents are outlined in this brief section. The selected tracks are the input for the jet clustering algorithms. Since jets are clustered solely from charged tracks they are referred to as *charged jets*. Track information can also be combined with calorimeter clusters and define jets with both a charged and neutral component (*full jets*). Full jets capture a larger fraction of the parton shower since they include the neutral component. The analysis presented in this thesis uses only charged jets.

The jets are defined by the jet finding algorithm (see Sec. 1.3). The main software tool for jet finding is the FastJet [146, 147] library which is used in AliPhysics [144] and includes fast native implementations of many sequential recombination clustering algorithms and tools for advanced jet manipulation. For this analysis, the jets were clustered with the anti- k_t algorithm [33] and the E-scheme as the recombination scheme. Both of these choices have been advocated as standard

for the study of jet physics in LHC Run 1 and 2 [207]. From the definition of the energy flow observable, it is evident that the variation of the jet cone radius is essential. In this work, jets were reconstructed with resolution parameters spanning from very small $R_{\text{jet}} = 0.05$ up to and including the most commonly used $R_{\text{jet}} = 0.4$, in steps of $\Delta R_{\text{jet}} = 0.05$.

The kinematic selections refer to the transverse momentum p_T and the pseudorapidity η of the jets. For Pb-Pb collisions, a requirement that the leading hadron of the jet has a momentum $p_T \geq 8$ GeV/c was implemented. This requirement reduces the effect of the underlying event and also provides a clean handle on the probed jet population. The same lower threshold was applied to the p_T of the jets analysed in the heavy-ion events. For pp collisions, only jets with $p_T > 10$ GeV/c were analysed to avoid the influence of soft jets in the matching between truth and reconstructed level and to minimize the computational time of the analysis. An additional selection of $p_T > 150$ MeV/c was applied on the tracks which were clustered into jets,

For pseudorapidity, a fiducial cut of $\eta_{\text{jet}} \leq 0.5$ is applied, corresponding to the coverage of TPC reduced by the radius of the largest considered jet $R_{\text{jet}} = 0.4$. In this way, partially reconstructed jets at the edges of the detector acceptance are excluded from the sample. This requirement mitigates the edge effects of the jet clustering algorithm which would reconstruct many jets at the edge region with ill-defined non-circular areas. This cut is applied on jets at the reconstructed level but not on the truth level jets which participate in the construction of the response matrix. With this configuration truth level jets outside the jet acceptance can still be matched to the detector level with $\eta_{\text{jet}} \leq 0.5$. Otherwise, the matched detector level jet would be treated as a fake jet and the missing truth level jet would contribute the kinematic efficiency correction of the measurements. In that scenario, the same edge effect would be considered twice. For the benefit of simplicity and the matching between wide and narrow jets, the same η selection is used for all of the jets regardless of R_{jet} . Furthermore the exclusion of partially reconstructed jets is achieved by the requirement that the jets in consideration have an area, A_{jet} , greater than 60% of their nominal cone area, πR_{jet}^2 .

Lastly, the reported distributions for each radial pair in the following chapters include a selection on the energy flow Δp_T and the jet p_T of the smaller of the two jets. This selection is based on the statistical uncertainties of the experimental and the stability of the unfolding procedure in that kinematic phase space (see Sec. 8.6). These criteria lead to different selections in the two collision systems for each radial jet pair.

8.5 Treatment of background contributions

In Pb-Pb collisions, there is a large background of uncorrelated particles that are included in the jet reconstruction and can inflate the measured jet p_T . The background contribution is made up from a median contribution and background fluctuations. The median contribution varies on an event-by-event basis. The background fluctuations refer to variations between different regions of the same event. The median background contribution is treated with the background subtraction methods, described in the following Sec. 8.5.1. On the other hand, the background fluctuations are more difficult to address. After the background subtraction the remaining background fluctuations are corrected through the unfolding procedure (Sec. 8.6). It should also be noted that due to the definition of the energy flow observable as Δp_T , the contributions of shared background fluctuations in the matched jets will balance out.

8.5.1 Background subtraction methods

The two methods that are most commonly applied in the field of heavy-ion jet analysis for background subtraction are the area-based or pedestal method [208, 209] and the constituent subtraction method [210]. In this analysis, the constituent subtraction method was preferred due to its enhanced performance in the removal of the background. Previous jet substructure investigations have arrived at similar findings.

The correction of the area-based method uses the median density of the background noise and the jet area. The latter component embodies the susceptibility of the jet contamination from diffuse noise. Since jets are comprised of point-like objects, the notion of jet area is non-trivial. For this purpose, a population of infinitely soft particles (ghost particles) is added in the event. The region in the rapidity and azimuth plane where the ghosts are clustered inside a jet corresponds to the jet area. The calculated jet area can differ significantly from the nominal cone area of πR_{jet}^2 [208]. For the calculation of the median background density it is important to distinguish between the soft particles in the event which act as noise and the fragments of the parton shower originating from the hard scattering. It has been found that jets clustered with the k_t jet finding algorithm [29, 30] reconstruct a large population of soft jets which do not represent any particular hard structure but rather organise a uniform background of soft particles into jets with a circular area (πR_{jet}^2) [209]. Therefore the jet population clustered with that algorithm, is utilised to calculate the background density ρ as the median of the ratios of the k_t -clustered jet p_T over its area [209]. With these two ingredients, the area-based background subtraction corresponds to the correction of the jet momentum by $\rho \cdot A_{\text{jet}}$ as

$$p_{T,\text{corr}} = p_{T,\text{raw}} - \rho \cdot A_{\text{jet}} \quad (16)$$

where A_{jet} is the area of the jet clustered with the anti- k_t algorithm.

The constituent subtraction method can be applied on an event-by-event basis. It is an extension of the area-based method that allows for a particle-by-particle correction. Similar to the pedestal method, this approach requires the addition of ghost particles and the calculation of the median background density. The number density of the added ghosts is one of the free parameters of the method and its inverse determines the area occupied from each ghost particle A_g . The transverse momentum of each ghost is defined as $p_T^g = \rho \cdot A_g$. For each jet constituent, the momentum corrections takes place iteratively. Specifically the distance in the $\eta - \phi$ plane is calculated for each pair of particle and ghost. These distances are sorted from lowest to highest. For each particle-ghost pair, the correction procedure starts from the closest match. Within a maximum distance ΔR_{max} , which is a free parameter of the method, the p_T of the softer of the two constituents is subtracted from the harder particle and then is set to zero. Once this process is repeated for all of the matched pairs, the particles with zero momentum are discarded and the jet finding algorithm is applied on the subtracted event. The advantage compared to the pedestal method is that the correction is done particle-by-particle so both the jet momentum and its substructure are corrected simultaneously. A more detailed account of the procedure and the performance of the technique in jet observables can be found in [210].

In this analysis, both of the methods were tested and the constituent subtraction method was preferred. This decision was based on measurements on the embedded Pythia8 MC sample (Sec. 5.4). Particularly, the evaluation metrics include: the influence of the background smearing on the observed jet energy flow distribution at the embedded detector level, the diagonality of the response matrix and the width of the jet energy resolution distribution ($p_{T,\text{embed}} - p_{T,\text{truth}}$). There are other methods which can be used to address the influence of the underlying event. One of

them is an iterative version of the constituent subtraction method which can further improve the results [211]. In previous research, the effect of background was investigated by the placement of cones with a random orientation in a heavy-ion event [212]. More recent results have showcased the advantage of the application of machine learning techniques to identify the correspondence between signal and measured jets in a heavy-ion environment [213].

8.6 Unfolding procedure

The unfolding procedure corrects a measured distribution for resolution effects. These are caused by the convolution of the true distribution with the response function. The latter term encodes the correspondence between the true and reconstructed value of a measurement. The aim of this procedure is to allow the comparison of the unfolded experimental measurement with model predictions or theoretical calculations. The correspondence between true and measured distribution is achieved in MC simulations through the jet tagging process (see Sec. 7.2). In this work, the jet energy flow was studied as a function of jet p_T , so there were a two-dimensional distribution at truth level and a corresponding one at reconstructed level. Therefore the binned detector response is represented by a four-dimensional matrix which can be visualized by partial projections in two dimensions.

Generally, the measured distribution M can be defined as,

$$M = R_M \times T, \quad (17)$$

where R_M is the response matrix and T represents the true distribution. The measured distribution may include entries which are not matched to entries in the true distribution (fake entries). In that scenario this fake entries have to be subtracted from the measured distribution. From Eq. 17, it follows that unfolding corresponds to the calculation of the inverse response matrix and its subsequent application to the measured distribution. If the response is purely diagonal, then unfolding becomes a a straightforward linear algebra exercise. However, in experimental measurements the response matrix is rarely diagonal since it is possible to have bin migrations between the true and measured distributions. In this case, a matrix inversion can lead to large un-physical fluctuations of the unfolded result. In this case, more complex algorithms than a matrix inversion are required. The two methods most widely used are the SVD algorithm [214] and the iterative Bayesian inference method [215]. Both of these algorithms are available in the RooUnfold [216–218] software library which is included in the AliPhysics software [144]. In the analysis presented in this thesis the Bayesian method was employed.

Evidently, the Bayesian inference method is based on the Bayes theorem [219] which estimates the probability of a true event given an observation and an assumption about the distribution of the true events. The latter is referred to as the prior distribution and in this work it is extracted from MC simulations. Furthermore through the iterative application of the Bayes theorem the assumed prior distribution is continuously updated. The unfolded distribution $\tilde{n}(C_i)$ is evaluated from the application of the inverse response matrix $P(E_j|C_i)$ to the measured distribution $n(E_j)$ as,

$$\tilde{n}(C_i) = \sum_{j=1}^{n_E} P(C_i|E_j)n(E_j), \quad (18)$$

where

$$P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\sum_{l=1}^{n_c} P(E_j|C_l)P_0(C_l)}. \quad (19)$$

The numerator of the response includes the probability of a truth value C_i given a measured value E_j , $P(E_j|C_i)$ and the prior distribution $P_0(C_i)$. The denominator is invariant between iterations and therefore acts as a normalization term. For a more in-depth discussion of the algorithm and especially the treatment of the uncertainties associated with binned distributions, the interested reader is directed to [220] and references therein.

There are multiple metrics and tests to evaluate the unfolding procedure and its stability. The validity of the unfolding procedure can be tested on MC samples where the true distribution is known. These tests are called closure tests and they can be performed to test the agreement either at the truth level or at the reconstructed level. The results of these closure tests for the analysis performed in this thesis can be found in Sec. 10.4 and 11.4 for pp and Pb-Pb collisions. Supplementary results of closure tests are included in the appendix of this thesis (Appendix A.2 and Appendix B.2).

The number of iterations in the Bayesian inference method is the regularization parameter that has to be tuned to avoid over-fitting of the distributions. The validation of the unfolding procedure includes the stability of the unfolded distributions as a function of the regularization parameter.

8.7 Sources of systematic uncertainty

The last ingredient of a measurement that is required prior to comparison with other experimental measurements or theoretical predictions is the evaluation of systematic uncertainties. These uncertainties encapsulate the effect of assumptions or choices that were made during the analysis process. To estimate the systematic uncertainties, a variation of the response matrix and subsequently the unfolded distribution is produced. The relative difference between the unfolded distributions produced from the default configuration and the outcome of the variation evaluated on a bin-by-bin basis corresponds to the systematic uncertainty assigned to that variation. The total systematic uncertainty is calculated as the quadratic sum of the individual systematic uncertainties from each source. In this analysis the following sources of systematic uncertainty were considered:

1. **Tracking efficiency:** The detector response is simulated using GEANT3 for detailed particle transport through the detector material and to reconstruct the generated MC events [154, 155]. The tracking efficiency is calculated through these simulations which take into account the geometry of the experimental apparatus. The determination of the tracking efficiency has an uncertainty that originates from the matching efficiency between data and MC as well as the agreement of the reconstructed tracks in the ITS and TPC detectors. It is important to calculate the effect of the tracking efficiency uncertainty in the measurement. In most jet analyses, this effect represents the source of the largest systematic uncertainty. The tracking efficiency uncertainty in pp collision is 3%. A random rejection of this percentage of tracks at the reconstructed MC level leads to the construction of a response matrix with a reduced tracking efficiency. For the analysis Pb-Pb collisions, 2% of the embedded Pythia tracks at the reconstructed level are already rejected in the default configuration. The purpose of this adjustment is to account for the reduced tracking efficiency of the detector in a high track density environment (see Sec. 5.4). For the calculation of the systematic uncertainty in the Pb-Pb measurement, an additional reduction in the order of 4% with a dependence on the p_T of the track is applied. The relative difference between the default unfolded distribution and the one produced by the response with the varied tracking efficiency was assigned as the systematic uncertainty

2. **Unfolding procedure:** The unfolding procedure is a complex process. The uncertainties primarily originate from the choice of the regularization parameter and kinematic feed-in and feed-out effects in the response function. Therefore multiple variations are considered in order to evaluate the related systematic uncertainty. The contributions from each variation are summed in quadrature. The systematic uncertainty due to the unfolding procedure corresponds to the ratio of the quadratic sum by the number of contributions. The considered variations are:
- (a) **Number of iterations, N_{iter} :** The number of unfolding iterations is the regularization parameter in the iterative Bayesian unfolding algorithm. Although a determination of the optimal value for this parameter is not always straightforward, its influence on the result is generally found to be small. For a stable unfolding procedure, the unfolded distribution should initially demonstrate an improvement as N_{iter} increases, followed by a relative plateau of stability and strong oscillations when the regularization parameter becomes too large. These oscillations occur because the algorithm tries to accommodate for the statistical fluctuations in the measured distribution. For the calculation of the systematic uncertainty a variation of ± 2 units around the nominal value was used.
 - (b) **Detector level truncation:** The unfolding phase space in terms of p_T and Δp_T is determined based on the statistical uncertainties of the experimental measurement and the stability of the unfolding procedure as established by the closure tests. A variation of the lower limit in the range of reconstructed jet p_T by ± 5 GeV/c is used to probe the sensitivity to the choice of unfolding phase space.
 - (c) **Prior distribution:** The shape of the prior distribution is one of the inputs to the unfolding procedure. The sensitivity to the shape of the prior distribution is explored by introducing an appropriate scaling. In this work, the prior Δp_T distribution of the default response was fitted with an exponential function. Two variations of the fitting function with 5% increased or decreased slope were evaluated. For each of these variations a response matrix was constructed where the prior distribution was scaled by the ratio of the modified over the original exponential fit function. The contribution of this variation to the systematic uncertainty was calculated as average of the relative difference between the default result and the unfolded distributions which used the modified prior distributions.
3. **Model dependence:** A source of systematic uncertainty which is not directly related to the unfolding process but influences the response matrix is the choice of the event generator. As discussed in Sec. 5.3 and 5.4, the default choice for the simulation of the jet signal is PYTHIA8 [152]. For pp collisions, an alternative model is HERWIG [221] which has a different hadronisation and parton shower implementation than PYTHIA8. For Pb-Pb collisions, an embedding scheme for HERWIG jets or JEWEL [110] simulations is a good alternative. Because no centrally produced Monte Carlo simulation with a full GEANT3 detector simulation is available for these models, a local event generation and detector parameterization was implemented ("fast simulation") [222, 223]. For the evaluation of the systematic uncertainty, a response matrix with this fast simulation was constructed for each of the models. The assigned systematic uncertainty corresponds to the relative difference between the data unfolded with the PYTHIA8 fast response and the fast response of the alternative models. In this way, any biases introduced by the parametrisation of the detector response are removed.

4. **Background subtraction method:** In the Pb-Pb measurement of this analysis the constituent subtraction method was employed to correct for the effect of the underlying event. This method has a free parameter ΔR_{max} (see Sec. 8.5.1), which was varied to explore the effect of over- or under-subtraction of the background contribution. In this analysis, the jet populations with $R_{\text{jet}} \leq 0.2$ were corrected with a $\Delta R_{\text{max}} = 0.1$ and the larger jets with $\Delta R_{\text{max}} = 0.25$. For the evaluation of the systematic uncertainty a variation to $\Delta R_{\text{max}} = 0.025$ and $\Delta R_{\text{max}} = 0.3$ was used. A measurement for each varied ΔR_{max} was carried out in both data and MC simulations. The resulting unfolded distributions were compared to the default measurement and their relative difference was assigned as the systematic uncertainty originating from the choice in the background subtraction method. This evaluation was not necessary in the pp measurement since there is no combinatorial background in that case.
5. **Leading track p_T cut:** For the analysis of Pb-Pb collisions, a selection on the transverse momentum of the jet's leading hadron was applied (see Sec. 8.4). Specifically, it was required that the hardest hadron of the reconstructed jets has a transverse momentum of $p_{T,\text{lead}^{\text{track}}} \geq 8$ GeV/c. This requirement was introduced to reduce the influence of fake jets reconstructed from the underlying event. This effect was confirmed by the improvement in the performance of MC closure tests. However, this selection introduces a bias in the analysis towards jets with a hard fragmentation pattern. In order to evaluate the sensitivity to this bias and to the remaining background, the analysis was repeated for data and MC samples which used a $p_{T,\text{lead}}^{\text{track}} \geq 10$ GeV/c cut. The relative difference of the unfolded distributions was assigned as the systematic uncertainty of this source. This procedure was not necessary for the measurement in the pp collisions since there was no equivalent requirement on the p_T of the leading hadron inside the jets. The effect of the leading track p_T cut in the comparison of jet energy flow measurements in pp and Pb-Pb collisions was investigated in JEWEL simulations and will be discussed in Sec. 13.3.

Part IV

Results & Discussion

9 JEWEL Jet Energy Flow Fluctuation (JEFF) Results

This chapter features the analysis results of the JEWEL Monte Carlo simulations which will serve as model comparisons for the ALICE JEFF measurement presented in the following chapters (Ch. 10 and Ch. 11). Sec. 9.1 explains the concept of recoil partons which is an important configuration option of the event simulation. The pseudorapidity and transverse momentum spectra of the jets are presented in Sec. 9.2. The distributions showing the spatial overlap between the matched jets are the topic of Sec. 9.3. The JEFF measurement in the three JEWEL simulation samples is presented in Sec. 9.4. Lastly, the sensitivity of these results to the presence of thermal medium background is investigated in Sec. 9.5.

9.1 Recoiling partons in JEWEL

In heavy-ion collisions, the measurements of jet observables and in particular jet substructure are sensitive to the medium response. In JEWEL, the partons within a jet interact with the partons of the background medium through $2 \rightarrow 2$ scattering processes described by perturbative matrix elements with associated gluon emissions from the parton shower. The treatment of the background partons that recoil (*recoils*) against the scattering with jet partons defines two distinct operational modes of the generator.

In one of these operational modes, the information on the recoils is not stored in the event record (*AA w/o recoil*). In this case, the model predictions can be directly compared with experimental background subtracted measurements. This mode favors simplicity against the more complicated experimental scenario. In the other mode, the recoils are kept in the event and hadronise along with the products of the initial hard scattering (*AA w recoil*). The recoils do not have further interactions with the background medium and free-stream to hadronization. In the hadronization stage, the recoil partons are converted to gluons and are color-associated with the hard jet partons from which they scattered. In this way, the recoil gluons are incorporated into the jet's string structure. Therefore a coherent contribution of the medium response is achieved and at the hadron level it is no longer possible to distinguish the hadrons that originate from a recoil or a hard scattering parton. The inclusion of the recoils introduces a thermal background contribution. This contribution has to be removed for comparisons with experimental measurements that include background subtraction. In JEWEL, the four-momenta of the medium partons before interactions with the jet can be written out in the event record for this purpose. At the analysis level this contribution has to be subtracted with background subtraction techniques that are applied on the constituent level such as the constituent subtraction method which was described in Sec. 8.5.1. Alternative methods which were devised specifically for JEWEL have been introduced in [156].

The exclusion of interactions between the medium and the recoil partons can be treated as a limiting case for the behavior of background partons. The opposite limit is the assumption of immediate thermalisation of the recoils which is employed by models which operate in the thermodynamic framework [224–227]. It is expected that a realistic recoil behavior lies somewhere between these two extremes, where the partons can have further interactions with the medium but do not fully thermalise.

9.2 Matched jet population

JEWEL MC events were simulated for proton-proton (*pp*) and heavy-ion collisions (*AA*). In the latter case, both of the operational modes of JEWEL with respect to the recoil partons were

explored. All of the events were simulated at a collision energy in the center of mass of $\sqrt{s} = 5.02$ TeV. The aim of the analysis is to study the energy flow within the parton shower as a function of the jet radius. Therefore the jet finding algorithm was applied for many values of R_{jet} ranging from very narrow cones ($R_{\text{jet}} = 0.05$) to wider jets ($R_{\text{jet}} = 0.4$). Prior to the analysis of JEWEL predictions for the jet energy flow observable (see Sec. 7.3), it is useful to look at the jet distributions in transverse momentum (jet p_T) and pseudorapidity (η).

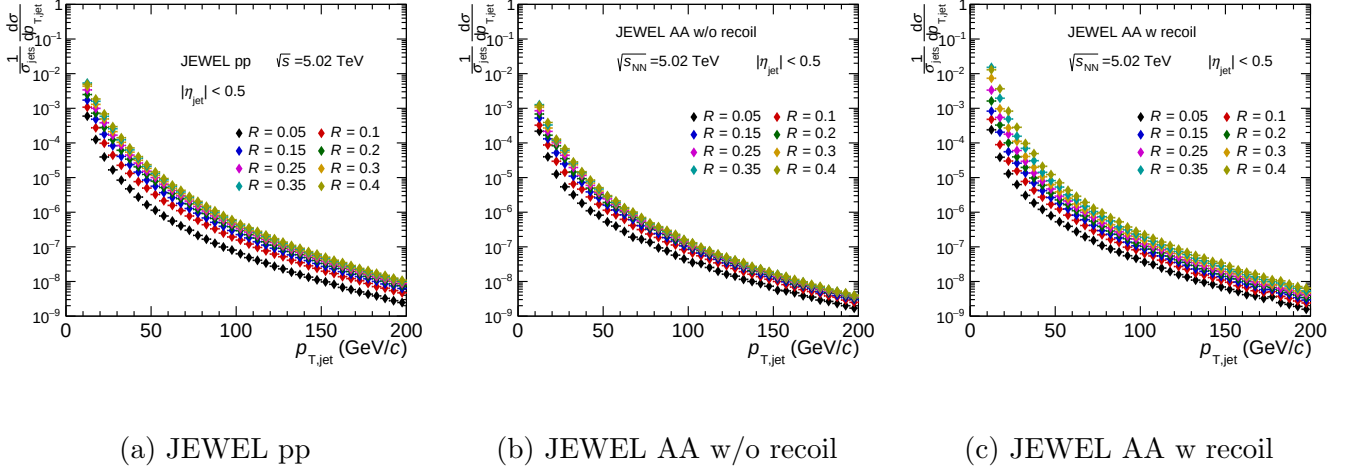


Figure 32: Jet p_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in JEWEL simulations of pp collisions (left), AA collisions without recoil (middle) and AA collisions with recoil (right).

The jet p_T distributions for all of the jet radii are displayed in Fig. 32. The left panel corresponds to the JEWEL simulation of pp collisions while the middle and right panels show the distributions for the JEWEL heavy-ion simulations in the AA w/o recoil and AA w recoil operational modes respectively. The background contribution in the latter case has been subtracted using the constituent background subtraction method. For all three cases, the distributions are steeply falling as a function of jet p_T following a power-law behavior. As the jet radius increases up until $R_{\text{jet}} \approx 0.2$ the spectrum becomes harder while this trend is not as clear for wider jets. Narrow jets are more likely to include less hadrons compared to their wider counterparts. In this way the difference in the slope of p_T spectra between narrower and wider jets is similar to the difference that has been observed between the momentum spectra of hadrons and jets.

The comparison of the p_T spectra for the two heavy-ion simulation modes shows that the inclusion of recoils in the event record primarily affects the low momentum region. Specifically, there is a broadening of the distribution in that region. The medium recoil particles tend to have low momenta so the broadening effect can be attributed either to background fluctuations or insufficient correction of the background contribution which allowed the clustering of "fake" thermal jets. The presented analysis in this dissertation takes place at higher momenta, outside the range of this effect. The effect of the recoil can also be seen in the nuclear modification ratios for the two modes which are shown in Fig. 33. From these distributions it is evident that the influence of recoils is more significant for large jets ($R_{\text{jet}} \geq 0.25$) where the model configurations diverge. For small jets, the two modes show good agreement for jets with $p_T \geq 30$ GeV/c.

Since the JEWEL predictions are intended as a comparison to the experimental measurements that will follow in the next chapters, a kinematic cut on the pseudorapidity of the tracks and jets

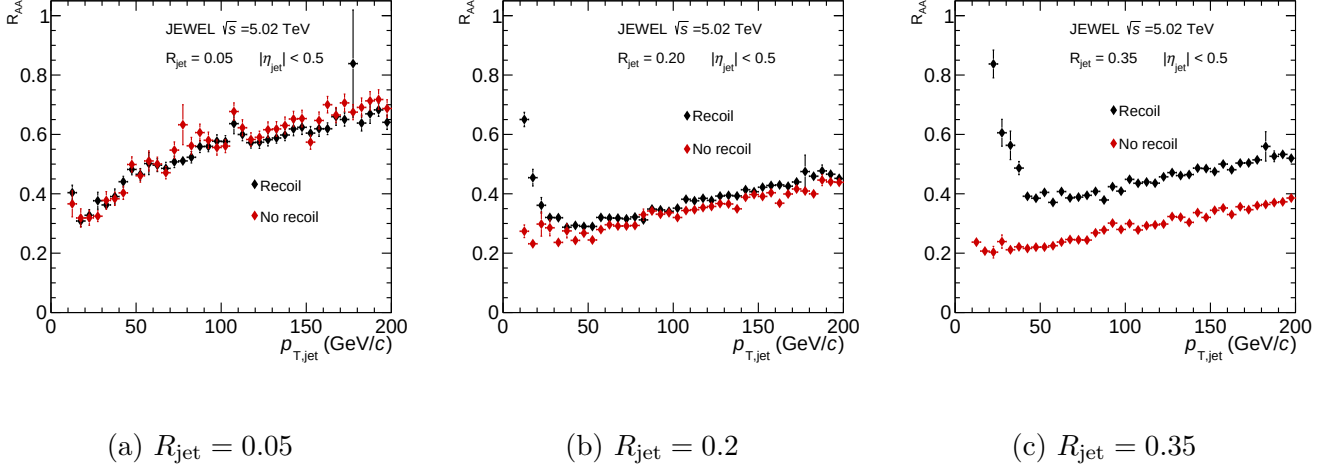


Figure 33: Nuclear modification factors for jets with radius $R_{\text{jet}} = 0.05$ (left), $R_{\text{jet}} = 0.2$ (middle) and $R_{\text{jet}} = 0.35$ (right) in JEWEL simulations for both recoil operation modes.

was applied. For the case of tracks, this cut was $|\eta_{\text{track}}| \leq 2$. For jets the η cut corresponds to the acceptance of the ALICE TPC subdetector reduced by the radius of the largest considered jet ($|\eta_{\text{jet}}| \leq 0.5$). See also Sec. 8.4 for more information. In Fig. 34, the pseudorapidity distributions of jets are presented for the three simulated collision systems. The distributions are close to uniform in the considered range.

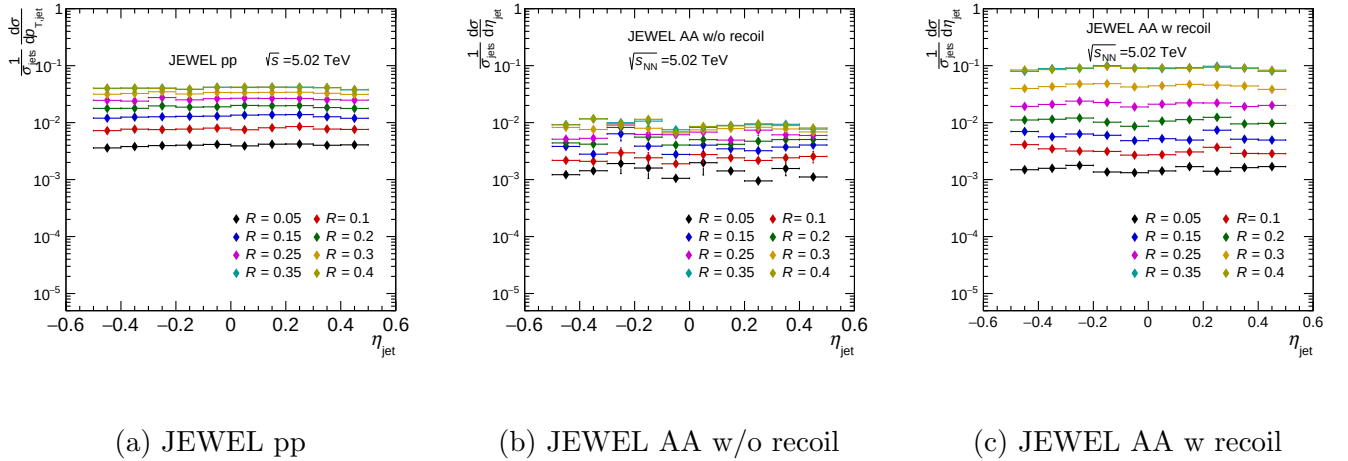


Figure 34: Jet η distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in JEWEL simulations of pp collisions (left), AA collisions without recoil (middle) and AA collisions with recoil (right).

9.3 Jet geometrical matching

An essential ingredient of the jet energy flow observable is the spatial overlap between the jets which are used to calculate the increase in the jet momentum. As described in Sec. 7.2, the criterion for the matching between a narrow ($R_{\text{jet},1} = R_0$) and wider jet cone ($R_{\text{jet},2} = R_0 + 0.05$)

is defined with respect to their distance on the $\eta - \phi$ plane,

$$\Delta R = \sqrt{(\eta_2 - \eta_1)^2 + (\phi_2 - \phi_1)^2}. \quad (20)$$

Naively, expanding the jet cone around a given parton shower would lead to co-centric jet cones after matching. In this case the distance (ΔR) in the $\eta - \phi$ plane between the jet axes for each matched jet pair would be $\Delta R = 0$. As it can be seen in Fig. 35, this expectation approximately holds since the distributions for all of the jet radial pairs in the three collision systems are falling very steeply. It should be noted that these distributions include a selection on the p_T of the narrower jet for each radial pair to be $60 \leq p_T < 80$ GeV/c.

With the matching procedure the closest match is selected but also an upper cut-off of $\Delta R_{max} = 0.2$ is included which clearly constrains the presented distributions. For all three cases of simulated events, an increase of the jet radius leads to a broader ΔR distribution. The matched pairs where $\Delta R > 0.05$ are a very small percentage. Furthermore, for small jet radii, a secondary peak towards large ΔR is also visible. However, as it can be seen by the size of the statistical error bars those matches are very few. These cases suggest that there is an increased probability for parton showers to be clustered in two separate jets of $R_{jet} = R_0$ and as a single jet of $R_{jet} = R_0 + 0.05$. In such a situation, since each jet match is unique, one of the smaller jets would be matched to a larger jet further away but still within the limits of the matching criterion. These special cases could be further investigated by including a selection on shared p_T fraction between the matched jets. In this thesis, it was deemed that the effect of those cases on the interpretation of the energy flow measurement is negligible considering their very small population. In addition, this secondary structure does not appear in the ΔR distributions of the matched jet pairs measured in the ALICE experimental data.

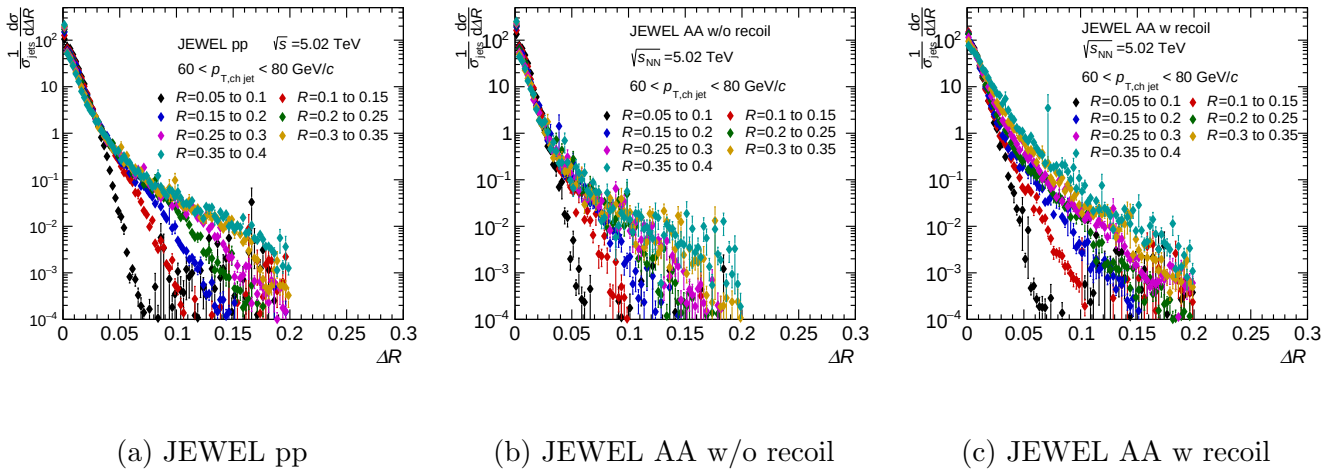


Figure 35: ΔR distributions between narrow and wider jets for radii between $R_{jet} = 0.05$ and $R_{jet} = 0.4$ in JEWEL simulations of pp collisions (left), AA collisions without recoil (middle) and AA collisions with recoil (right).

9.4 JEFF distributions

For each pair of jet radii $R_{jet,1} = R_0$ and $R_{jet,2} = R_0 + 0.05$, the energy flow in terms of $\Delta p_T = p_{T,2} - p_{T,1}$ is calculated for each of the matched jet pairs. With a selection of $60 \leq p_{T,1} < 80$

GeV/c on the transverse momentum of the narrow jet in each radial pair, the Δp_T distributions are extracted. These are presented in Fig. 36 for all seven of the radial pairs in the three collision systems.

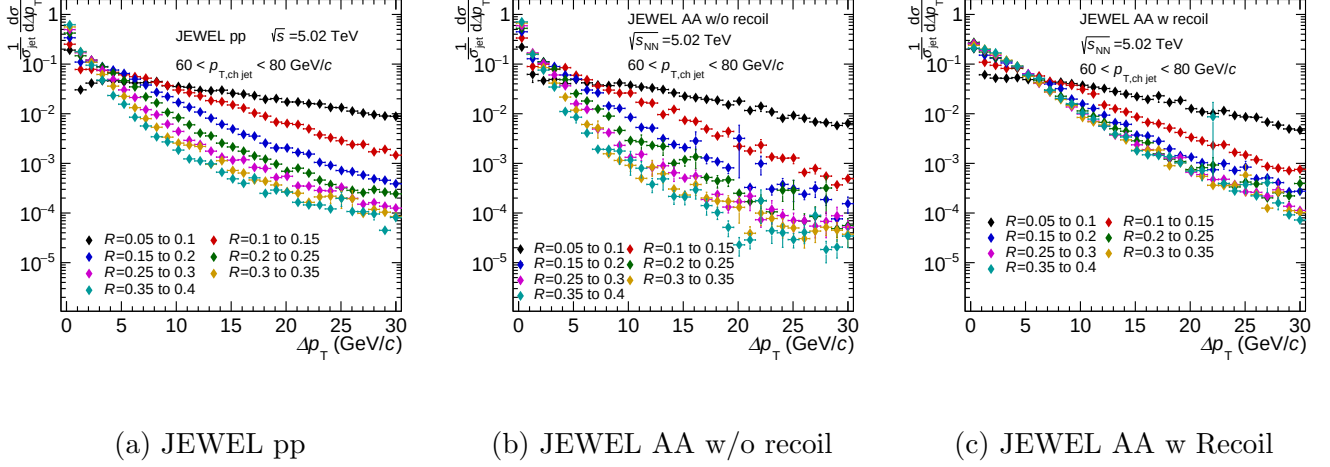


Figure 36: Δp_T distributions between narrow and wider jets for radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in JEWEL simulations of pp collisions (left), AA collisions without recoil (middle) and AA collisions with recoil (right).

All of these distributions exhibit a distinct peak at $\Delta p_T = 0$ and a steeply falling distribution as Δp_T increases. In the majority of the matches, the small expansion of the jet cone around the parton shower does not yield an increase in the jet momentum. Furthermore a smooth transition towards steeper distributions as function of the jet radius is observed. This feature is more evident in the cases of JEWEL pp collisions (Fig. 36a) and in the AA collisions where the medium response is ignored (Fig. 36b). If the information of the recoil partons is maintained in the event record, then the increase in the steepness of these distributions seems to saturate for $R_{\text{jet}} \geq 0.2$ (Fig. 36c).

The modification of the Δp_T distributions in the presence of the medium can be seen more clearly in Fig. 37 which shows a comparison of selected Δp_T distributions between AA and pp collisions for the smallest ($R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$), the largest ($R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$) radial pair and an intermediate cone size ($R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$). The respective plots for the rest of the examined jet radial pairs can be found in Appendix C.1. In all three cases, the distribution for the smallest jet radial pair exhibits a sharp drop between the first and second bin and a relatively flat tail towards larger Δp_T (Fig. 37a). This feature indicates that jets with small opening angles may probe the core of the parton shower. This is where the majority of the momentum is concentrated. With the increase of the jet radius, the energy flow distributions become steeper in AA collisions without recoil information compared to the other two cases. For the case of the largest radial pair, the presence of recoils leads to broader Δp_T distribution compared to the vacuum reference (Fig. 37c).

The above observations about the evolution of the jet Δp_T as a function of the jet cone radius can be summarised by comparing the mean and the standard deviations of the Δp_T distributions. The results are presented in Fig. 38. Both of these measures exhibit a similar behavior as a function of the jet radius.

For the case of pp collisions, the mean energy flow as well as its fluctuations are decreasing with the expansion of the jet cone around the parton shower. This pattern is in agreement with

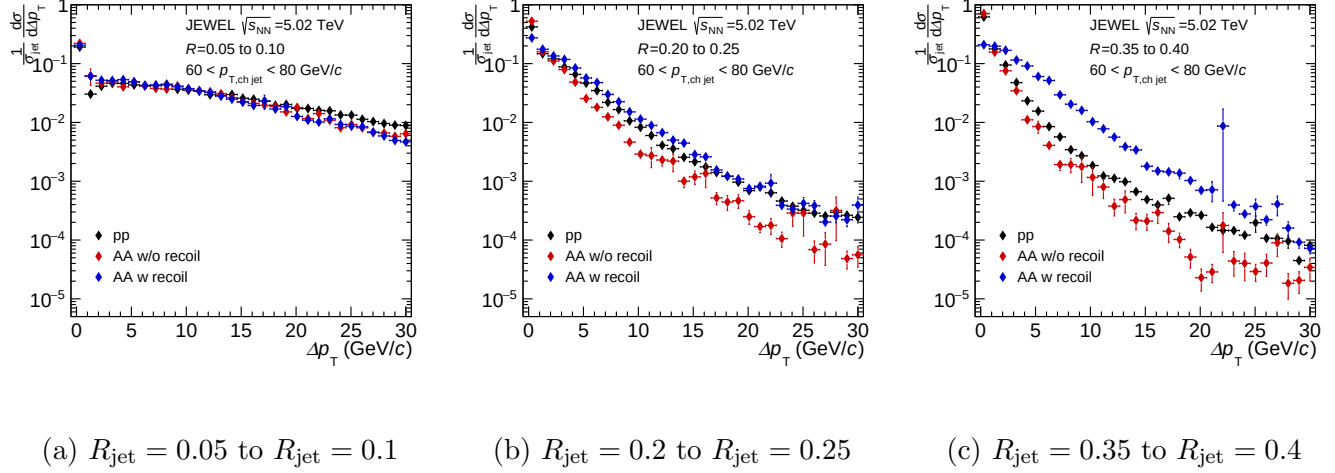


Figure 37: Δp_T distributions for the smallest ($R_{\text{jet}} = 0.05$ (left) to $R_{\text{jet}} = 0.1$), intermediate ($R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$) (middle) and the largest ($R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$) (right) radial pair in JEWEL simulations of pp collisions, AA collisions without recoil and AA collisions with recoil.

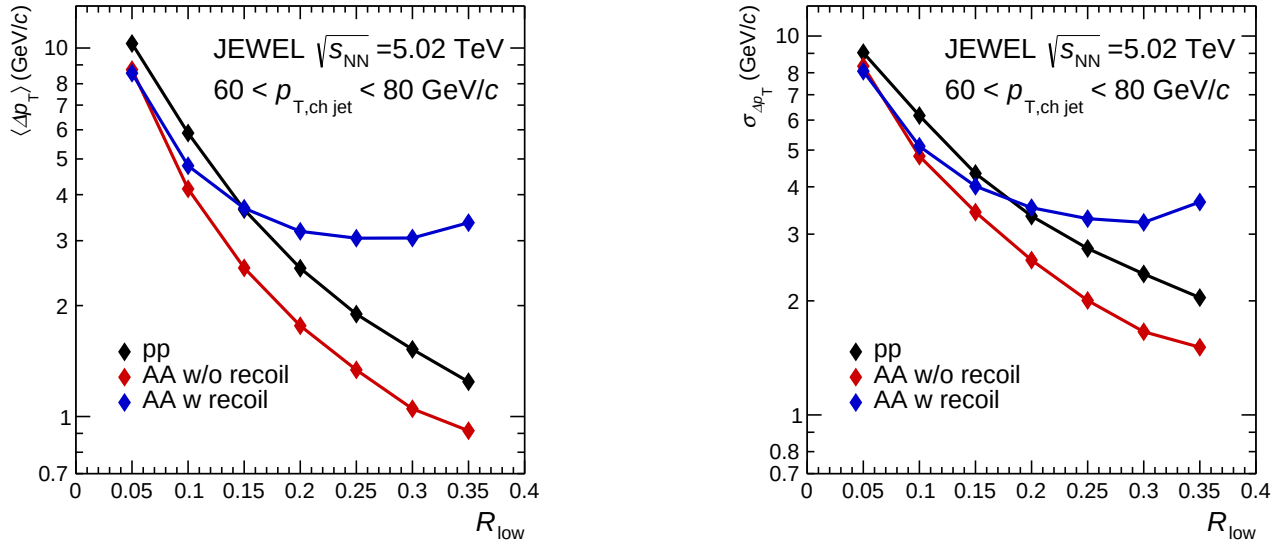


Figure 38: Dependence of the mean energy flow and its standard deviation on the jet radius for JEWEL simulations of pp and AA collisions with or without recoil partons.

the expectation that the majority of the jet energy is concentrated close to the jet axis and the particles at the edge of the jet cone have a small contribution. In heavy-ion collisions the same behavior is observed when recoil partons are not considered. However, due to parton energy loss, the increase in the jet momentum is smaller compared to the vacuum case. This observation implies a narrowing of the jet energy profile in AA collisions. For small jet radii, $R_{\text{jet}} \leq 0.15$, the contribution of recoil partons in the mean energy flow and its standard deviation is small and both curves lie below the vacuum prediction. However as the jet radius increases the inclusion of the

medium response becomes gradually more important, leading to an increase and a large difference between the predictions of the two JEWEL AA operational modes at larger R .

Particularly, for the AA with recoil case towards large radii a transition from a decreasing to a saturated and even increasing jet energy flow is observed. This increase may be due to recapture of energy which has been re-distributed to large angles. On the other hand, the continuous decrease of the energy flow for the AA collisions without recoil may point towards a larger energy loss for wide parton showers. The latter would be motivated by medium-induced incoherent gluon radiation and resolution of the jet structure by the medium. Independently of the interpretation, the JEWEL predictions for the jet energy flow indicate that the observable is sensitive to jet quenching (predictions in pp vs AA collisions) as well as to the effect of the medium response (AA w/o recoil vs AA w recoil).

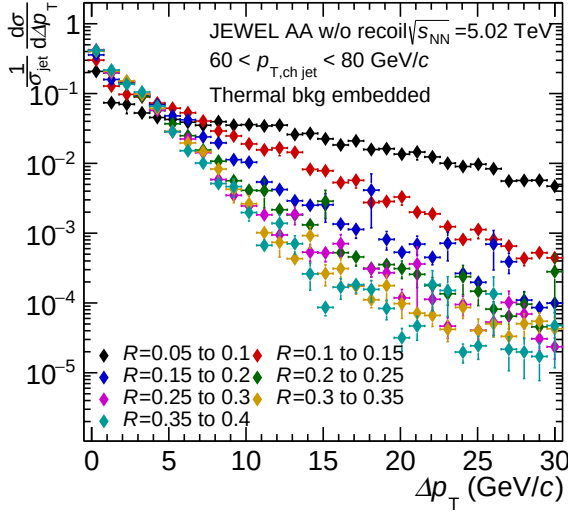
9.5 JEWEL embedding in thermal background

The JEWEL model simulates the evolution of a parton shower in the presence of an externally provided medium but not the full heavy-ion event. However the experimental measurements in heavy-ion collisions, even with the application of background subtraction techniques, are susceptible to the presence of the underlying event and its fluctuations. Therefore it is important to investigate the robustness of the observable's discriminatory capability in the presence of a thermal medium. For this purpose, an ensemble of JEWEL AA collisions for both recoil operational modes was simulated and embedded in a thermal medium. The transverse momentum of the thermal particles follows a Boltzmann distribution with mean $p_T = 700$ MeV/c. After embedding, the clustered jets are corrected with the constituent background subtraction method. In correspondence to Fig. 36, the energy flow distributions for the embedded AA collisions with and without the recoil partons for all of the jet radial pairs are presented in Fig. 39.

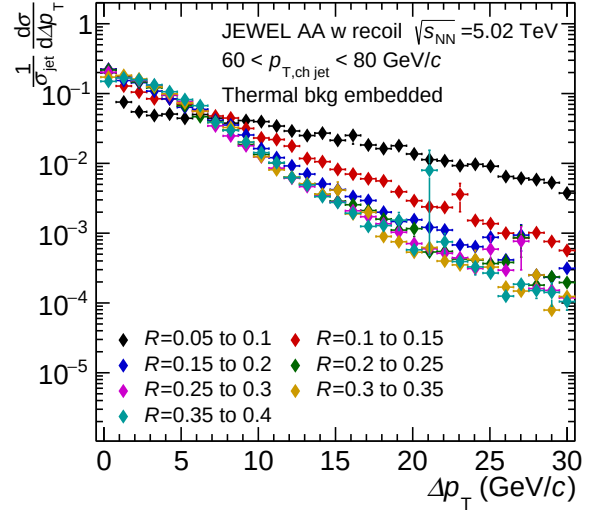
The Δp_T distributions for the thermal embedded JEWEL events exhibit the familiar steeply decreasing behavior. The peak at $\Delta p_T = 0$ can still be recognized however the feature is less distinct than in the distributions presented in the previous section. The effect of the thermal smearing becomes more evident in the examination of the mean energy flow and its standard deviation as a function of the jet radius. From Fig. 40, it is clear that the effect of the thermal medium is stronger in the larger jets.

Especially for the case of AA without recoils, the presence of the thermal medium leads to a deviation from the continuously decreasing trend. This feature is qualitatively similar to the evolution of the energy flow in the case of AA collisions with recoils in the absence of thermal embedding. It is worth noting that these distributions have not been corrected for the effect of background fluctuations through an unfolding procedure. That approach will be followed in the analysis of experimental measurements in both pp and Pb-Pb collisions presented in the following chapters. Therefore, the intention in this section is to highlight the robustness of the observable in the examined range of jet radii with respect to the thermal background.

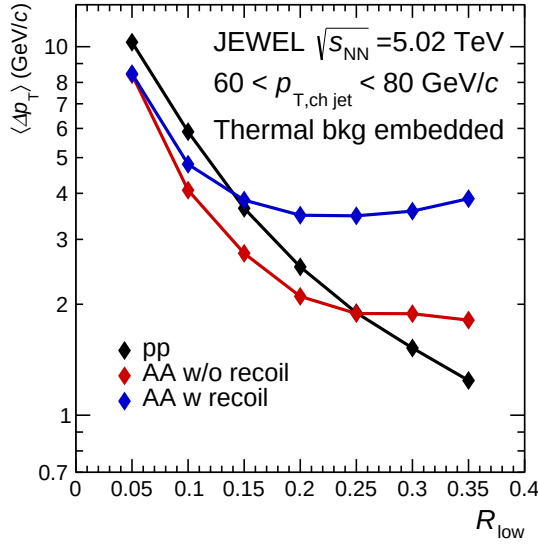
To summarize, the Δp_T distributions are smeared with the inclusion of a thermal medium which approximates the effect of recoils for large jets. However, the discrimination power of the observable with respect to the collision system and the influence of the recoil particles is maintained.



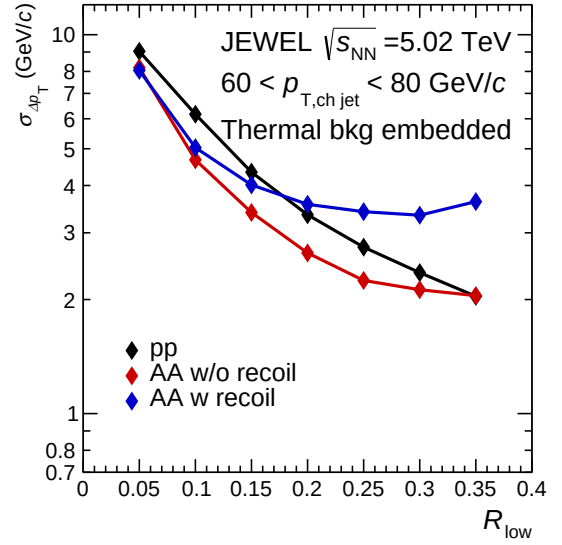
(a) Thermal embedded JEWEL AA w/o Recoil



(b) Thermal embedded JEWEL AA w Recoil

 Figure 39: Δp_T distributions between narrow and wider jets for radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in JEWEL simulations of AA collisions without recoil (left) and AA collisions with recoil (right) embedded in a thermal medium.


(a) JEWEL mean energy flow collision system comparison after embedding



(b) JEWEL energy flow fluctuations collision system comparison after embedding

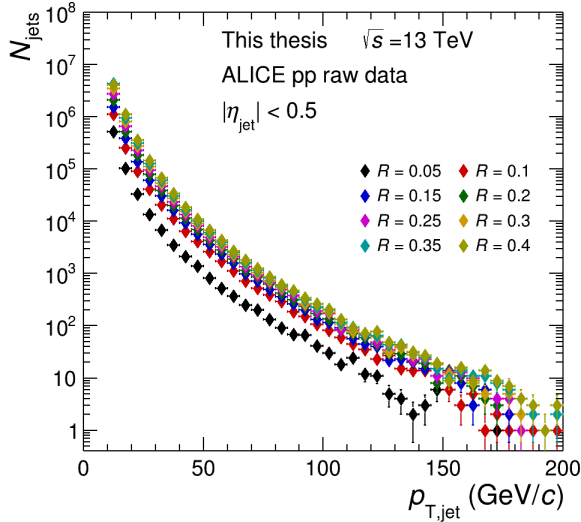
Figure 40: Dependence of the mean energy flow and its standard deviation on the jet radius for JEWEL simulations of pp and AA collisions with or without recoil partons embedded in a thermal medium.

10 ALICE pp JEFF Results

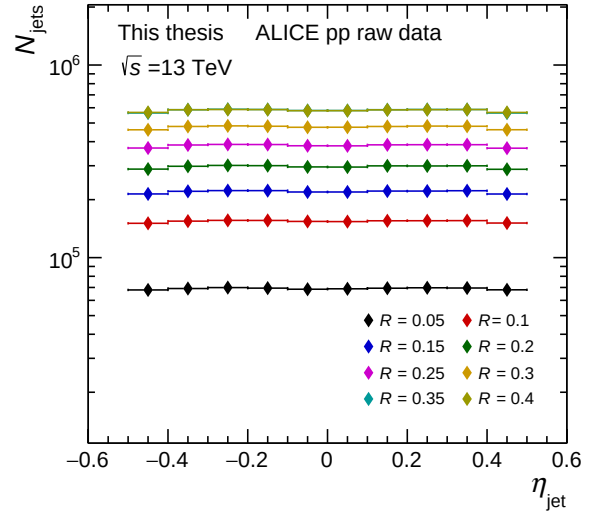
This chapter is dedicated to the jet energy flow measurement in pp collisions with the ALICE experiment. The results will be compared to the corresponding measurement in Pb-Pb collisions (Ch. 11) in order to study jet quenching. In this way, the jet energy flow measurement in pp collisions serves as a reference. The distributions in pseudorapidity and transverse momentum of the jets that are analysed in the measurement are presented in Sec. 10.1. In Sec. 10.2, the ΔR distributions between the matched jets show their spatial overlap. The initial energy flow measurements in ALICE data (Sec. 10.3), after corrections (Sec. 10.4) and the evaluation of systematic uncertainties (Sec. 10.5) transform them into the complete measurement in ALICE pp collisions (Sec. 10.6).

10.1 Matched jet population

The transverse momentum and pseudorapidity distributions for the jet population analysed in the energy flow measurement in ALICE pp data are shown in Fig. 41. The jet p_T distribution (Fig. 41a) shows that there is a sufficiently large statistical sample between $40 \leq p_{T,\text{jet}} < 60$ GeV/c and $60 \leq p_{T,\text{jet}} < 80$ GeV/c, which is the intended range of the energy flow measurement. The depicted jet p_T spectra are characterised by a steeply falling shape which follows a power-law function. As the jet radius increases, up until $R_{\text{jet}} \approx 0.2$, the spectrum becomes harder, while this trend is not as clear for wider jets. These characteristics were also present in the jet p_T spectra of the JEWEL simulations (Sec. 9.2).



(a) Jet p_T distribution



(b) Jet η distribution

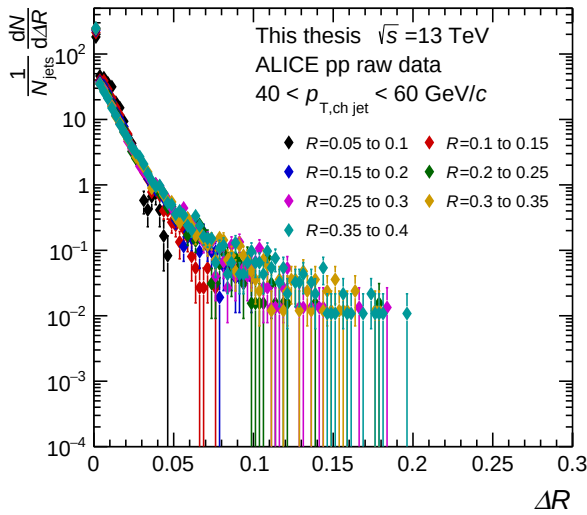
Figure 41: Distributions of jet p_T (left) and η (right) for matched jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE data of pp collisions at $\sqrt{s} = 13$ TeV.

The pseudorapidity distributions are shown for the jet radii in the range from $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.4$ in Fig. 41b. Within the considered range of $|\eta_{\text{jet}}| \leq 0.5$ the distributions are uniform.

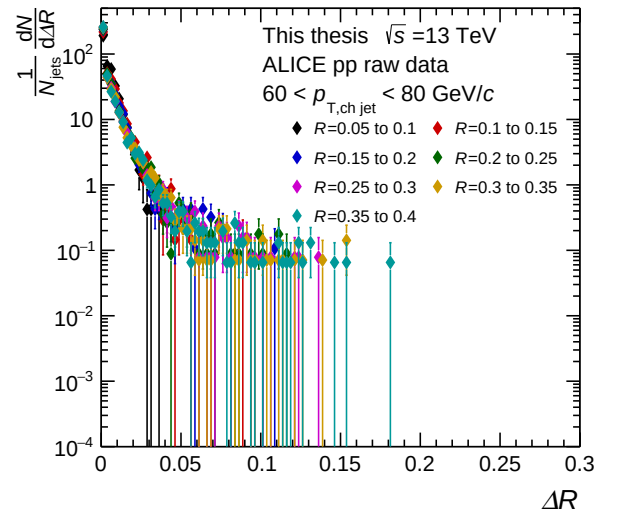
This kinematic cut corresponds to the acceptance of the ALICE TPC subdetector reduced by the largest considered jet radius.

10.2 Jet geometrical matching

For the calculation of the jet energy flow, each narrow jet is matched bijectively with a wider one through the procedure described in Sec. 7.2. The key element in the matching procedure is the distance between the axes of the jets in the $\eta-\phi$ plane, ΔR . The ΔR distributions for the matched jet pairs in ALICE pp data for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ are shown in Fig. 42. These distributions include a selection on the p_T of the narrow jet in each matched pair to be $40 \leq p_T < 60$ GeV/c (Fig. 42a) or $60 \leq p_T < 80$ GeV/c (Fig. 42b).



(a) Selection: $40 \leq p_T < 60$ GeV/c



(b) Selection: $60 \leq p_T < 80$ GeV/c

Figure 42: ΔR distributions between narrow and wider jets for radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE data from pp collisions at $\sqrt{s} = 13$ TeV. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c (left) and $60 \leq p_T < 80$ GeV/c (right).

These distributions are self-normalized while taking into account the bin width. It is evident that the majority of the matched jet pairs are in the region where $\Delta R < 0.05$. This confirms that there is significant overlap between the jet cones for the jet populations analysed in the energy flow measurement. Lastly, within the available statistical accuracy there is no secondary peak structure at large ΔR as it was observed in the JEWEL simulations (Fig. 35).

10.3 JEFF distributions

The energy flow measurement in ALICE pp data prior to the corrections and introduction of systematic uncertainties is presented in Fig. 43. The Δp_T distributions for each pair of jet radii from $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ include a selection on the transverse momentum of the narrow jet. This selection is $40 \leq p_T < 60$ GeV/c for Fig. 43a and $60 \leq p_T < 80$ GeV/c for Fig. 43b.

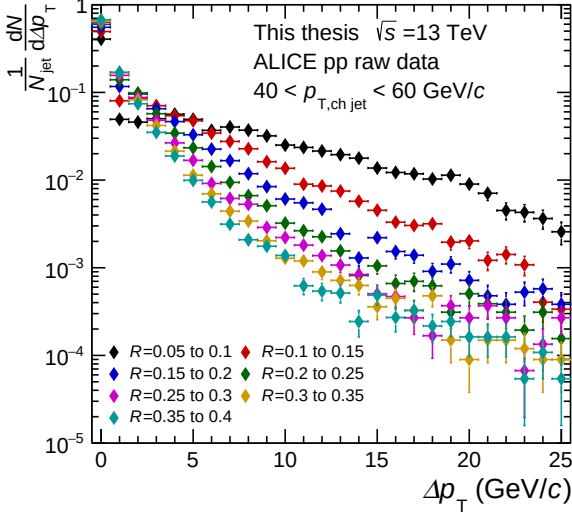
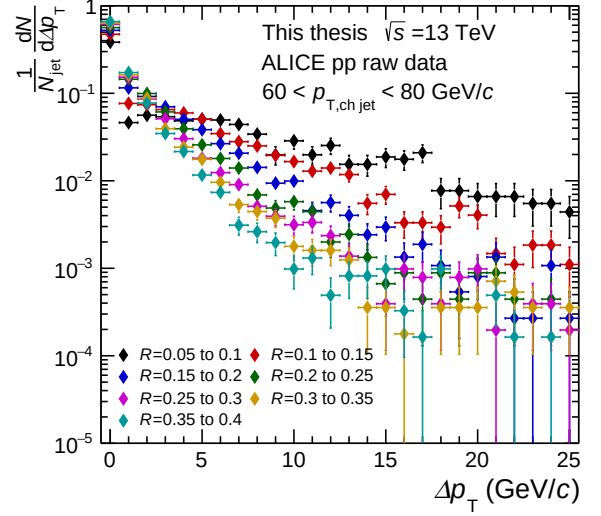
(a) Selection: $40 \leq p_T < 60$ GeV/c(b) Selection: $60 \leq p_T < 80$ GeV/c

Figure 43: Measured Δp_T distributions prior to detector effect corrections for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE data from pp collisions at $\sqrt{s} = 13$ TeV. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c (left) and $60 \leq p_T < 80$ GeV/c (right).

In all of these distributions a distinct peak at $\Delta p_T = 0$ is present, followed by a steeply falling curve. The steepness of the distributions increases smoothly through the transition from smaller to larger jet radii. It is evident that for $R_{\text{jet}} \geq 0.1$, the increase of the jet radial cone does not lead to an increase in transverse momentum ($\Delta p_T = 0$) in the majority of cases. For the smallest radial pair, the first bin has the leading contribution to the measurement. A closer investigation of the jet distribution within this first bin revealed that the overwhelming majority of the cases correspond exactly to $\Delta p_T = 0$.

In order to illustrate the dependence of the Δp_T distributions on the jet radius more clearly, some of the distributions shown in Fig. 43 are repeated in Fig. 44. For each of the two selections in jet p_T , the distribution of the smallest radial pair, $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (black) is considerably broader and flatter compared to the other distributions. This may indicate that jets with this small radius probe the substructure of the hard core of the parton shower. The distributions for intermediate size jets, $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ (green) and the widest considered in this analysis $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ (cyan), lie close to each other but remain distinct. The difference in the radius size between the three curves is the same but the distributions for intermediate and large jets share a more similar shape. Lastly, the dependence of the energy flow distributions on the jet p_T between 40 GeV/c and 80 GeV/c appears to be mild.

10.4 Corrections

The energy flow distributions which were presented in the previous section have to be corrected for the effect of the detector response. This section is dedicated to the procedures which were used to qualify and benchmark these corrections. In ALICE PYTHIA simulations the analysis proceeds

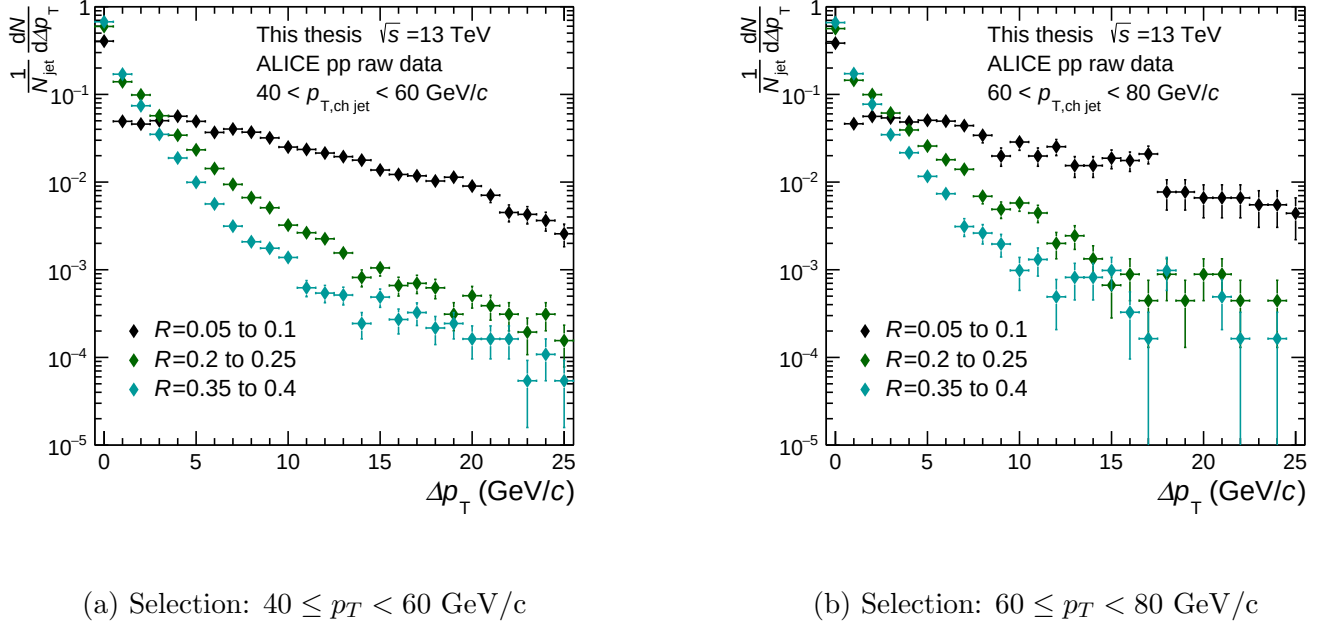


Figure 44: Measured Δp_T distributions prior to detector effect corrections for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.1$ (black), $R_{\text{jet}} = 0.2$ and $R_{\text{jet}} = 0.25$ (green), and $R_{\text{jet}} = 0.35$ and $R_{\text{jet}} = 0.4$ (cyan), in ALICE data from pp collisions at $\sqrt{s} = 13$ TeV. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c (left) and $60 \leq p_T < 80$ GeV/c (right).

as follows:

- Jets are clustered at the reconstructed and the truth level.
- At the reconstructed level, jets of different radius are matched and their Δp_T is calculated.
- Jets at the reconstructed level are also tagged with a suitable candidate at the truth level (See Sec. 7.2)
- At the truth level, for each $R_{\text{jet},1} = R_0$, jets which have a tagged counterpart at the reconstructed level are matched with jets at the truth level of radius $R_{\text{jet},2} = R_0 + 0.05$ and the corresponding Δp_T is calculated.

This procedure establishes the correspondence between the energy flow at truth and reconstructed level. Jet energy flow is measured as a function of the energy of the narrower counterpart in each radial pair. For that reason, the manifestation of the above correspondence as a response matrix is a 4-dimensional object taking into account the two observables at generator and detector level. For the benefit of visualisation, projections of this object to one or two dimensions are needed.

The two-dimensional projections of the response matrix in terms of jet energy are presented in Fig. 45 for narrow $R_{\text{jet}} = 0.05$, intermediate $R_{\text{jet}} = 0.2$ and wide jets $R_{\text{jet}} = 0.35$. Furthermore these distributions have been normalized by row so that each horizontal line represents a probability distribution for the reconstructed jet energy. In all three cases a clear diagonal structure is observed with the rest of the jet population confined in the upper left region of the plot. These are cases where some of the jet energy is missing at the reconstructed level as a result of finite

detector reconstruction efficiency and acceptance. The accurate reconstruction of jet momentum, probability of the diagonal bin, is more likely for jets with a small radius with low or intermediate jet momenta.

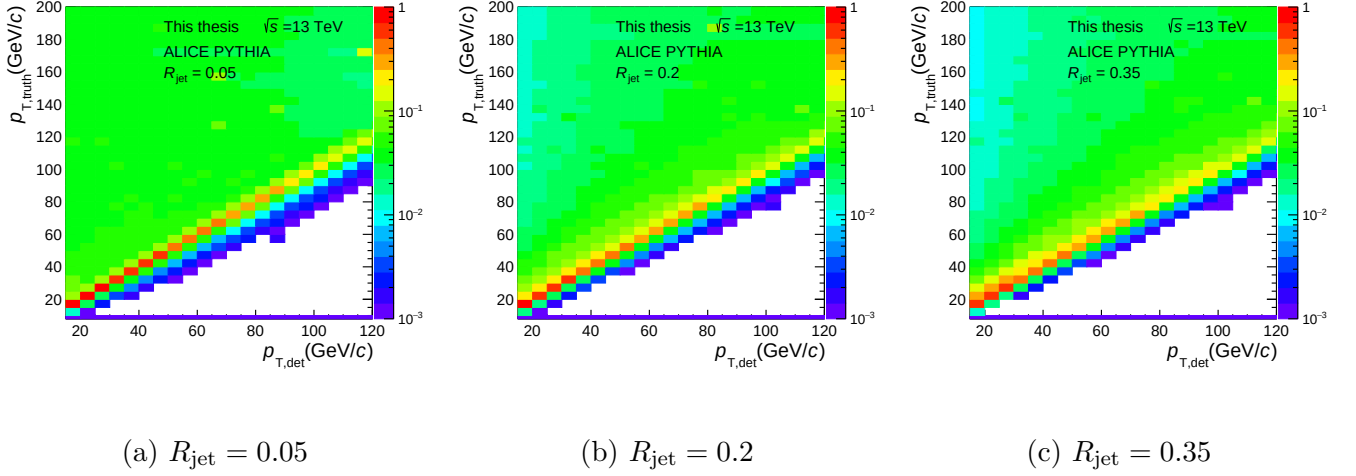


Figure 45: Projections of the response matrix for the jet p_T between truth and detector level in ALICE PYTHIA simulations for jets with radius $R_{\text{jet}} = 0.05$ (left), $R_{\text{jet}} = 0.2$ (middle) and $R_{\text{jet}} = 0.35$ (right).

The response matrix projections for Δp_T at generator and detector level for jet energy selection of $60 \leq p_T < 80$ GeV/c are presented in Fig. 46. Similarly to the response projections of the jet energy a clear diagonal structure is observed for all three jet radial pairs. A similar normalization per row has been applied to reflect a probability distribution for the Δp_T reconstruction at detector level. For the case of the wider jet pair, $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$, a secondary structure begins to appear at $\Delta p_T = 0$ at detector level regardless of the truth level value. A possible source of this artifact could be cases where the matched wider jet at detector level does not correspond to the matched wider jet at particle level. The magnitude of this secondary peak is small enough not to raise a concern for the unfolding process.

A complementary visualisation of the detector response is by one-dimensional distributions of relative difference in jet momentum for each truth level jet (*jet energy response*) and the difference in their energy flow (*jet energy flow resolution*). These two resolution distributions for truth level jets with $60 \leq p_T < 80$ GeV/c are presented in (Fig. 47a) and (Fig. 47b), respectively.

For the jet energy response plot, the distributions show a peak at zero which means there is no bias in the reconstruction of the jet momentum. The width of the distributions reflects the detector resolution of jet energy reconstruction and defines the minimum bin width for the measurement. The jet energy response distribution is clearly asymmetric towards the negative side, i.e. towards cases where some energy is missing at the reconstructed level. The asymmetric shoulder is broader for larger jet radius and it exhibits a smooth dependence on the R_{jet} . In the jet energy flow resolution distribution an asymmetry towards negative difference is also present but less pronounced compared to the energy response curve. In addition, the distributions for all jet radii are narrower with a strong dependence on jet radius. For the presented distributions a selection on the energy of the jet at generator level is applied, $60 \leq p_T < 80$ GeV/c. The corresponding distributions for a jet selection of $40 \leq p_T < 60$ GeV/c are shown in Appendix A.1 along with the respective response matrix projections.

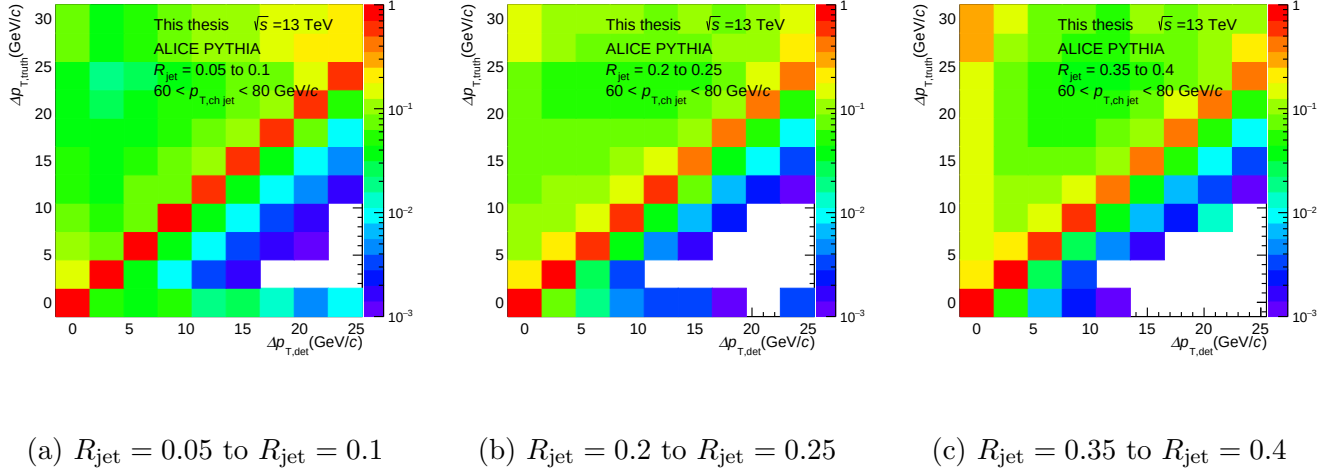


Figure 46: Projections of the response matrix for Δp_T between truth and detector level in ALICE PYTHIA simulations for matched jet pairs with radius $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (left), $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ (middle) and $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ (right). In all three panels a selection on the narrow jet's p_T at truth level, $60 \leq p_T < 80$ GeV/c, is applied.

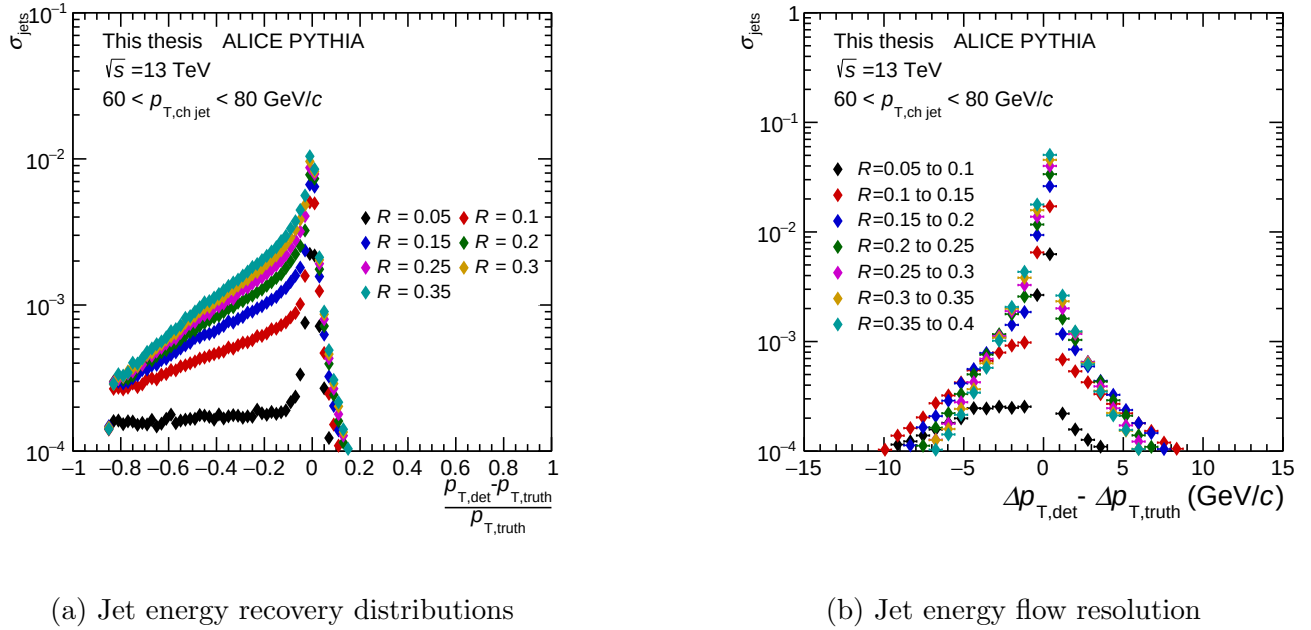


Figure 47: Jet energy resolution (left) and Δp_T resolution (right) plots for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE PYTHIA simulations. For both plots a selection on the jet p_T of the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

With the response matrices determined in ALICE PYTHIA simulations the energy flow measurements in data are corrected through the unfolding procedure. The unfolding method used in this work is the iterative Bayesian inference [215]. Prior to the unfolding of the experimental measurement the robustness and reliability of the unfolding method can be established through closure tests. In closure tests, the unfolding procedure intended for experimental data is applied to

simulated events where the truth level distribution is known. Two types of closure tests have been performed. The first one refers to closure tests on the truth level where the simulated data at the detector level are unfolded and compared with the truth level distributions. In closure tests, the simulated data are separated into two subsets, where one of them is used for determination of the response matrix while the other plays the role of a test sample. If these two samples are identical then the test is called a *trivial closure test*. For a trivial closure test, perfect agreement between the unfolded and the truth level distribution is expected to confirm the numerical stability of the unfolding process. In the more interesting case where the two subsets are different, agreement within the statistical uncertainties is expected.

The performance of closure tests at the truth level for three radial size pairs is shown in Fig. 48. A selection on the jet energy of the narrow jet of each radial pair $60 \leq p_T < 80$ GeV/c, is applied. Although there is some bin-by-bin fluctuation of the unfolded result, sufficient closure is observed for all three jet radial pairs. In addition, the stability of the unfolded result with respect to the number of unfolding iterations, which is a free parameter in the unfolding method, is also visible.

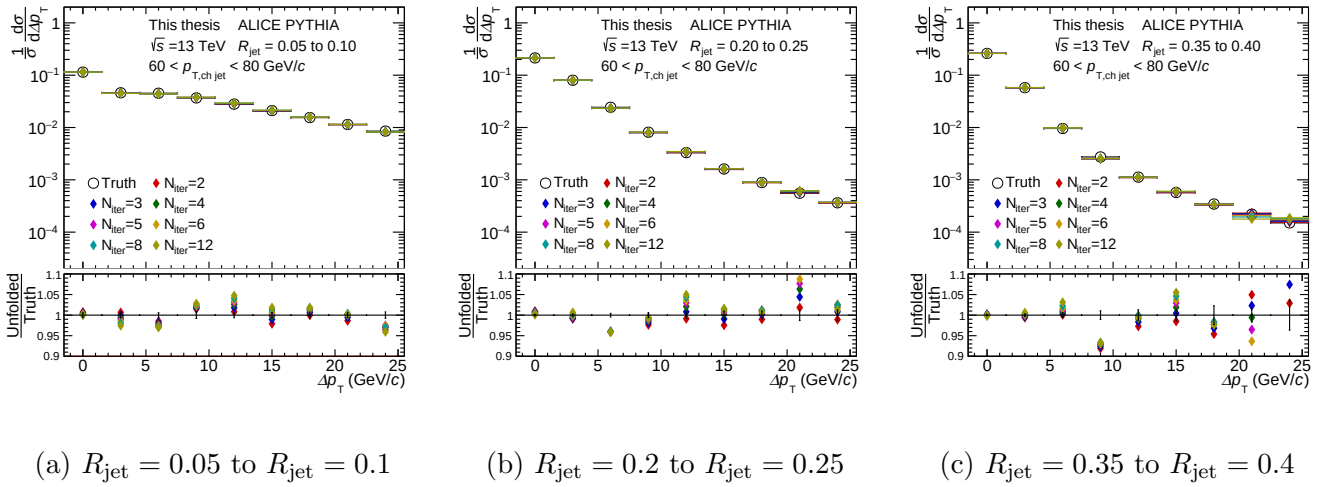


Figure 48: Performance of closure tests at the truth level for Δp_T distributions for jet pairs with radius $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (left), $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ (middle) and $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ (right) in ALICE PYTHIA simulations. The bottom panels show the ratio between the unfolded and truth level distributions. In all three panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

Closure tests can also be performed on the reconstructed level, which establish the reversibility of the unfolding procedure. For this type of closure tests, the unfolded distribution is treated as the true distribution and can be re-folded by applying the response matrix. The refolded distribution is then compared with initial detector level distribution that was used as an input for the unfolding procedure. Similar to the closure tests at truth level, trivial closure tests can be performed with the use of the same dataset for the response matrix construction and as input pseudodata. In the case that different data samples are used, the performance of closure tests at the reconstructed level is presented in Fig. 49 for three jet radial pairs. A selection on the jet energy of the narrow jet of each radial pair $60 \leq p_T < 80$ GeV/c, is applied. The stability of the closure test convergence as a function of the number of iterations was also examined. For all of the examined cases sufficient closure is observed with small fluctuations on a bin-by-bin basis.

The presented correction procedures and closure tests were performed for all of the examined

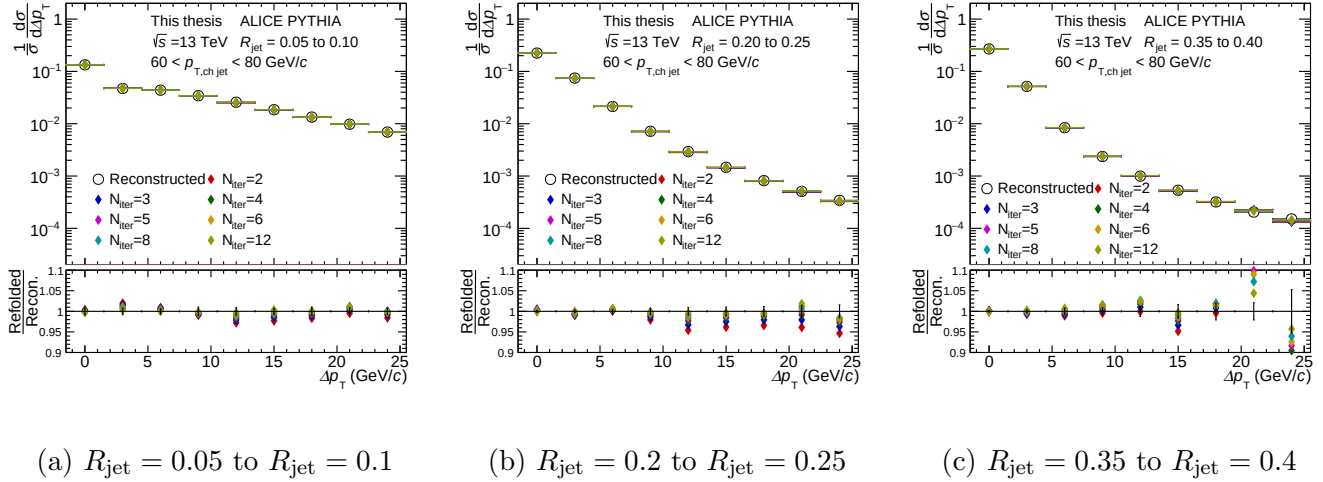


Figure 49: Performance of closure tests at the reconstructed level for Δp_T distributions for jet pairs with radius $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (left), $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ (middle) and $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ (right) in ALICE PYTHIA simulations. The bottom panels show the ratio between the refolded and detector level distributions. In all three panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

jet radii in both of the jet p_T ranges of $40 \leq p_T < 60$ GeV/c and $60 \leq p_T < 80$ GeV/c. For the benefit of brevity only a selection of those results was presented in this chapter. Further closure test results for the jets measured in this analysis can be found in [Appendix A.2](#). To summarize, satisfying performance was observed for all of the examined jet radii in both jet p_T ranges. This validated unfolding procedure was applied to the correction of the energy flow measurement in the ALICE pp data. The unfolded distributions with the inclusion of the systematic uncertainties discussed in the next section make up the final ALICE measurement of the observable in ALICE pp collisions.

10.5 Sources of systematic uncertainty

Systematic uncertainties are related to the assumptions of the analysis method and the experimental setup used in the energy flow measurement. This sensitivity is explored through variation of the choices and assumptions made during the analysis procedure. These calculations were performed for each of the seven examined pairs of jet radii in both jet p_T ranges of $40 \leq p_T < 60$ GeV/c and $60 \leq p_T < 80$ GeV/c. The uncertainties are estimated based on the relative ratio of the systematic variations on a bin-by-bin basis with the assumption of a smooth dependence of the uncertainty on Δp_T .

For the energy flow measurement in pp data, the investigated sources of systematic uncertainties are the tracking efficiency, the unfolding parameter choices and the assumed input distribution for the calculation of the detector response. The uncertainty of the tracking efficiency originates from the accuracy in the matching process of tracks between the various sub-detectors of the setup. This uncertainty is propagated to the energy flow measurement by the simulation of a response matrix where 3% of the tracks have been randomly rejected. This new response matrix is then used to unfold the measured distribution and compared to the default unfolded distribution. The relative ratio of this systematic variation is used for the estimation of the corresponding systematic uncertainty.

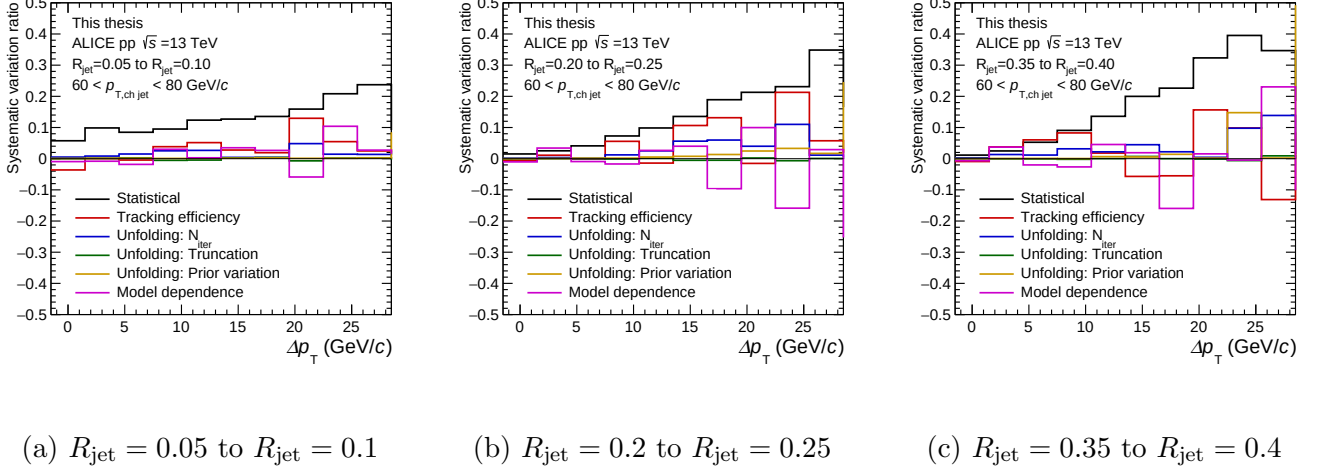


Figure 50: Overview of the relative systematic variation ratios for the smallest radial pair(left), intermediate and the largest radial pair(right) examined. A selection to the jet p_T , $60 \leq p_T < 80$ GeV/c, of the narrow jet has been applied. The statistical uncertainty of the default unfolded distribution is also plotted as a reference.

The systematic uncertainty of the unfolding process is estimated through the variation of a few key aspects of the process. Specifically, these contributions refer to a variation of the regularization parameter which is the number of unfolding iterations, N_{iter} , a variation of the lower limit of jet p_T at detector level and a variation of the prior distribution. For the regularization parameter an unfolded distribution with a higher and lower number of iterations was calculated and the average of the two relative differences from the default unfolded result was assigned as the systematic variation ratio. The variation of the momentum threshold at detector level by 5 GeV/c in the determination of the response matrix is used to estimate the systematic uncertainty of the momentum truncation. The last variation contributing to the unfolding systematic uncertainty is related to the shape of the prior truth level distribution. To estimate this uncertainty, the truth level distribution of the response matrix is fitted with an exponential function. Two variations of the fitting function are then calculated with their slope modified by $\pm 5\%$. For each of these two functions a modified response matrix is calculated by re-scaling the prior distribution with the ratio of the modified over the original exponential fit function. Through this process, two response matrices with a flatter and steeper truth level distributions compared to the default response are created. The average of the relative differences between the unfolded results with these variations and the default unfolded measurement constitutes the basis for the estimation of systematic uncertainty from this variation. A total systematic uncertainty for the unfolding procedure is calculated as the quadratic sum of the uncertainties from each variation divided by the number of contributions.

Lastly the dependence on the MC generator used for the construction of the response matrix was evaluated by comparing the unfolded results based on PYTHIA and HERWIG simulations. Since no GEANT3 simulation is available with the HERWIG event generator, the systematic variation was calculated by comparing the unfolded results from a detector response for PYTHIA and HERWIG samples using a parameterized efficiency and momentum resolution [223]. The corresponding systematic uncertainty was estimated on the basis of the relative difference between the distributions unfolded with the two parameterized responses.

The total systematic uncertainty is calculated as the quadratic sum of the individual systematic

Systematic Uncertainties $\backslash$ $R_{\text{jet}}^{\text{small}}$ to $R_{\text{jet}}^{\text{large}}$	0.05 to 0.1	0.1 to 0.15	0.15 to 0.2	0.2 to 0.25	0.25 to 0.3	0.3 to 0.35	0.35 to 0.4
Tracking efficiency	2 – 4%	1 – 4%	1 – 3%	1 – 2%	2 – 3%	1 – 3%	1 – 3%
Unfolding: N_{iter}	0 – 1%	0 – 2%	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 1%
Unfolding: Prior variation	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 2%	0 – 4%	0 – 3%
Unfolding: Jet p_T truncation	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 1%
Model dependence	1 – 3%	1 – 2%	1 – 5%	1 – 4%	2 – 4%	2 – 3%	3 – 4%
Total	2 – 5%	1 – 5%	1 – 6%	1 – 5%	2 – 5%	1 – 5%	3 – 5%

Table 3: Overview of the systematic uncertainties for the energy flow measurement in ALICE pp data at the jet p_T range of $40 \leq p_T < 60$ GeV/c. The columns correspond to the seven examined jet radial pairs between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$. The percentage range in each field indicates the lower and upper limits of the uncertainty in the reported Δp_T range.

Systematic Uncertainties $\backslash$ $R_{\text{jet}}^{\text{small}}$ to $R_{\text{jet}}^{\text{large}}$	0.05 to 0.1	0.1 to 0.15	0.15 to 0.2	0.2 to 0.25	0.25 to 0.3	0.3 to 0.35	0.35 to 0.4
Tracking efficiency	3 – 4%	0 – 3%	0 – 5%	1 – 6%	1 – 4%	2 – 3%	1 – 4%
Unfolding: N_{iter}	0 – 2%	1 – 2%	0 – 1%	0 – 4%	1 – 4%	1 – 5%	1 – 5%
Unfolding: Prior variation	0 – 1%	0 – 1%	0 – 2%	0 – 2%	0 – 2%	0 – 2%	0 – 2%
Unfolding: Jet p_T truncation	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 1%	0 – 1%
Model dependence	1 – 3%	1 – 4%	1 – 3%	2 – 5%	3 – 5%	2 – 10%	3 – 10%
Total	3 – 5%	1 – 5%	1 – 6%	2 – 8%	3 – 7%	3 – 11%	3 – 11%

Table 4: Overview of the systematic uncertainties for the energy flow measurement in ALICE pp data at the jet p_T range of $60 \leq p_T < 80$ GeV/c. The columns correspond to the seven examined jet radial pairs between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$. The percentage range in each field indicates the lower and upper limits of the uncertainty in the reported Δp_T range.

uncertainties for each source. For the benefit of brevity a selection of the systematic ratios from each variation is displayed in Fig. 50 for three jet radial pairs in the jet p_T range of $60 \leq p_T < 80$ GeV/c. The respective overviews for the rest of the jet radial pairs as well as for the jet selection of $40 \leq p_T < 60$ GeV/c can be found in Appendix A.3. A comprehensive list of all of the examined cases are presented in the Tables. 3 and 4, where the columns represent the radial pairs and the ranges correspond to the dependence in Δp_T . From both the figure and the tables it is evident that systematic uncertainties of the tracking efficiency and model dependence are the most significant.

10.6 ALICE pp JEFF measurement

This section features the complete jet energy flow measurement in ALICE pp data and in that way corresponds to the culmination of the analysis effort described in the rest of this chapter.

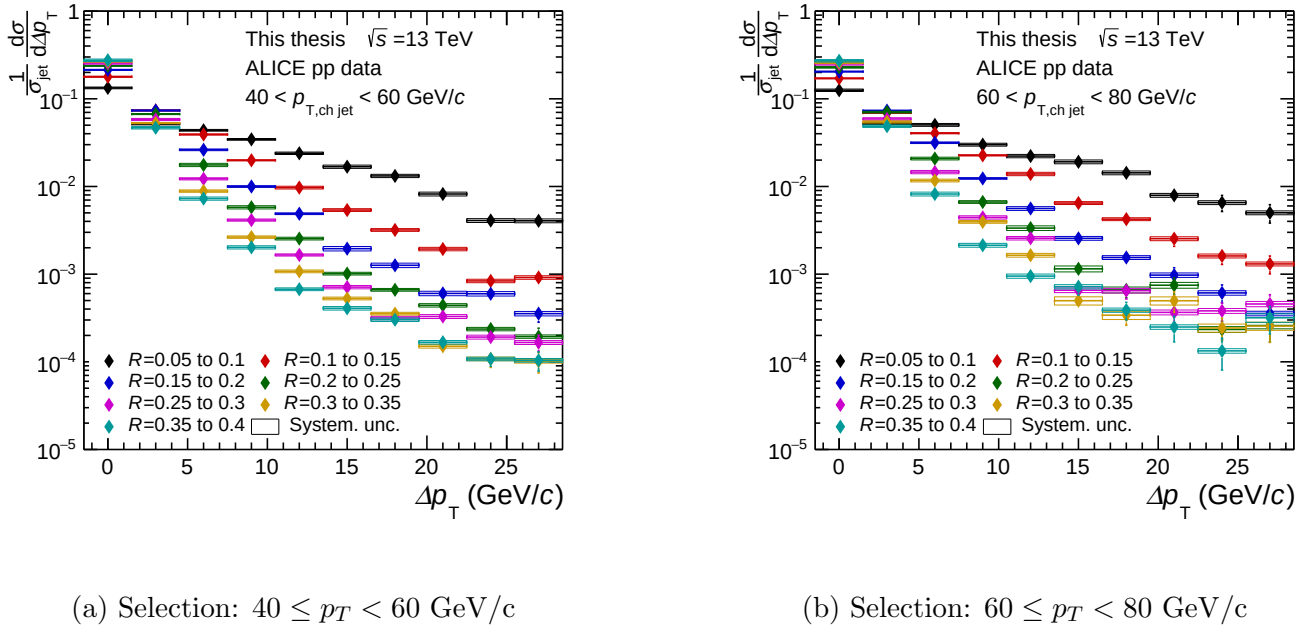


Figure 51: Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE data from pp collisions at $\sqrt{s} = 13$ TeV. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c (left) and $60 \leq p_T < 80$ GeV/c (right).

An overview of the jet energy flow distributions for each of the seven jet radial pairs between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in the jet p_T ranges of $40 \leq p_T < 60$ GeV/c and $60 \leq p_T < 80$ GeV/c is shown in Fig. 51. Following the unfolding corrections, the distributions have maintained their steeply falling shape. In addition, there is still a smooth transition from flatter to steeper curves as the investigated jet radius increases. This observation holds in both of the examined jet p_T ranges. For all of the cases, the systematic uncertainties are under control and do not exceed the level of statistical uncertainty. For the benefit of clarity, a selection on the smallest, intermediate and largest jet radial pair for both jet p_T ranges is presented in Fig. 52. For both ranges of the jet momentum the energy flow is systematically larger for the smallest jet radius pair of $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$. These small jet radii probe the core of the parton shower, where most of the jet energy is concentrated. In addition, the other two distributions for the energy flow from $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ and $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ are significantly closer to each other.

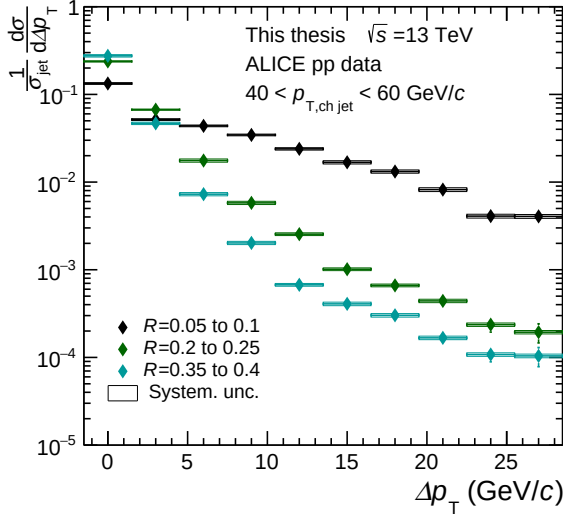
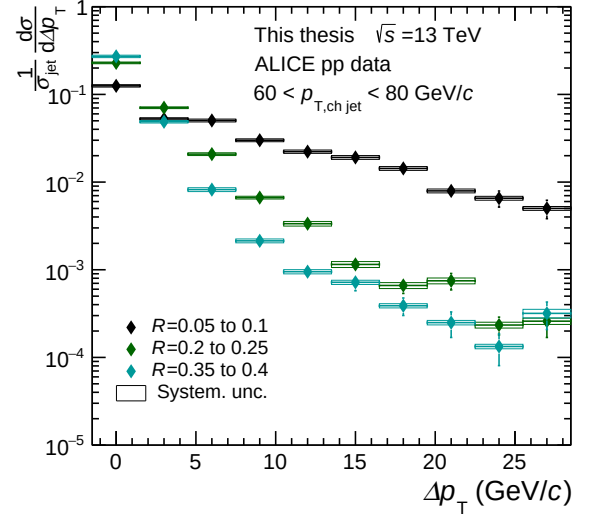
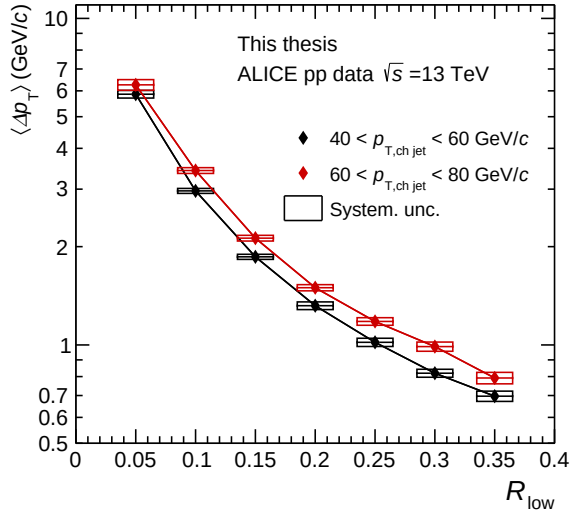
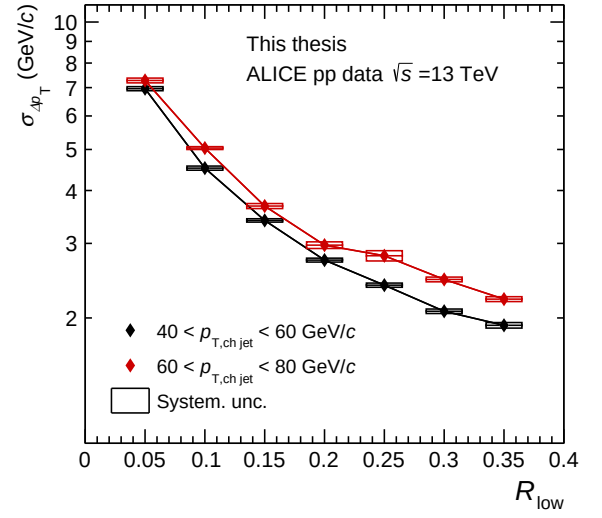
(a) Selection: $40 \leq p_T < 60$ GeV/c(b) Selection: $60 \leq p_T < 80$ GeV/c

Figure 52: Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.1$ (black), $R_{\text{jet}} = 0.2$ and $R_{\text{jet}} = 0.25$ (green), and $R_{\text{jet}} = 0.35$ and $R_{\text{jet}} = 0.4$ (cyan), in ALICE data from pp collisions at $\sqrt{s} = 13$ TeV. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c (left) and $60 \leq p_T < 80$ GeV/c (right).

The evolution of jet energy flow as a function of the jet radius is quantified by examining the mean and standard deviation of these distributions. Both of these observables are shown in Fig. 53, for both jet p_T ranges: $40 \leq p_T < 60$ GeV/c and $60 \leq p_T < 80$ GeV/c. For both of the measures a subtle dependence on the jet momentum is observed. Furthermore, the mean energy flow and its fluctuations are decreasing with increasing jet radius. The concentration of the energy flow in the small jet radii points towards the collimated nature of these parton showers. This behaviour is also seen in the jet energy flow in JEWEL pp simulations which was presented in Fig. 38. These measurements serve as reference to study the effect of jet quenching in Pb-Pb collisions which are presented in the next chapter.



(a) Mean energy flow



(b) Energy flow standard deviation

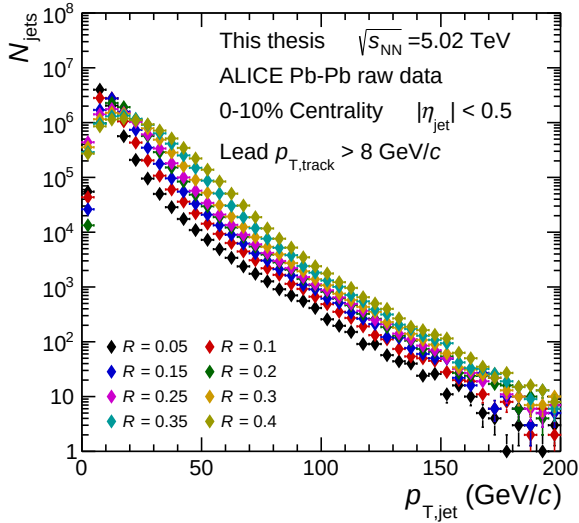
Figure 53: Measurement of the mean Δp_T (left) and its fluctuations (right) as a function of the R_{jet} in ALICE pp data, for two jet p_T ranges: $40 \leq p_T < 60$ GeV/c (black markers) and $60 \leq p_T < 80$ GeV/c (red markers).

11 ALICE Pb-Pb JEFF Results

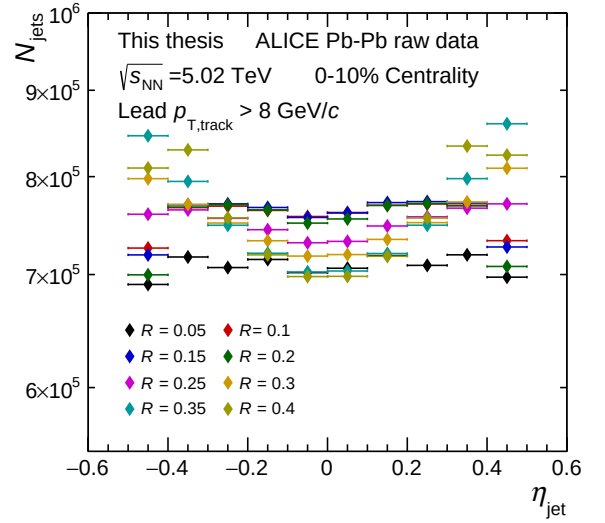
The jet energy flow measurement in Pb-Pb collisions with the ALICE experiment is described in this chapter. Following the presentation of some basic kinematic jet distributions in Sec. 11.1, the ΔR and raw data Δp_T distributions of the matched jet pairs are shown in Sec. 11.2 and 11.3, respectively. Sec. 11.4 is dedicated to the corrections that are applied in the experimental measurement of the jet energy flow distributions. The systematic uncertainty contributions are shown in Sec. 11.5 just before they are included in the complete ALICE Pb-Pb measurement, introduced in Sec. 11.6.

11.1 Matched jet population

The measured distributions for the jet p_T and η in Pb-Pb collisions with the ALICE experiment are shown in Fig. 54. These measurements correspond to the 10% most central collisions and include a pseudorapidity cut of $|\eta_{\text{jet}}| \leq 0.5$. Furthermore, an additional requirement on the p_T of the leading track, $p_{T,\text{track}}^{\text{lead}} \geq 8 \text{ GeV}/c$, is applied. The presented distributions correspond to jet populations with radius between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$.



(a) Jet p_T distribution



(b) Jet η distribution

Figure 54: Distributions of jet p_T (left) and η (right) for matched jets with radii $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE data of Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.

The jet p_T spectrum follows a steeply falling power-law shape, similar to JEWEL simulations (Sec. 9.2) and ALICE pp data (Sec. 10.1). However, in the low p_T region, the spectrum exhibits a broader peak or shoulder, which is more prevalent in the case of wider jets. This effect can be attributed to the uncorrelated background. A similar effect was observed in the case of JEWEL simulations embedded into a thermal background medium. The depicted jet populations are extracted after the background contribution has been subtracted with the constituent method. However the statistical fluctuations of the background create a smearing effect on the jet p_T . This effect leads to a broad, almost Gaussian shape of the spectrum close to $p_T = 0$. To correct for

the remaining background fluctuations an unfolding technique is applied. Additionally, in order to reduce the background contamination, the energy flow measurement in Pb-Pb only uses the p_T region of $60 \leq p_{T,\text{jet}} < 80$ GeV/c.

The jet pseudorapidity distribution measured in Pb-Pb collisions is shown in Fig. 54b. The distributions are close to uniform in the considered range. For larger jet radii, an increased yield towards the edges of the acceptance is observed. This structure was not present in the corresponding distribution in ALICE data of pp collisions. One difference between the two cases is that in heavy-ion collisions there is a higher track occupancy of the detector which may be related to this edge effect. Furthermore, this edge effect for the case of tracks has also been observed in earlier ALICE studies supported by MC simulations. Follow-up investigations revealed that these tracks at the edge of the acceptance originate from the uncorrelated background and not the hard scattering. These fluctuations are notable particularly for larger jets with radius of $R_{\text{jet}} > 0.25$. The increased population of large jets at the edges of the distribution leads to large $d\eta$ and therefore large ΔR distances between them and the matched jets of smaller radius. The jet radius dependence of this effect is shown in the following section.

11.2 Jet geometrical matching

The distance ΔR in the $\eta - \phi$ plane between the axes of two matched jets is calculated with Eq. 20 and as it was mentioned in Sec. 7.2 plays a key role to the identification of the jet pairs and the calculation of the jet energy flow. For each radial pair, a distribution of the distances between the matched pairs is shown in Fig. 55.

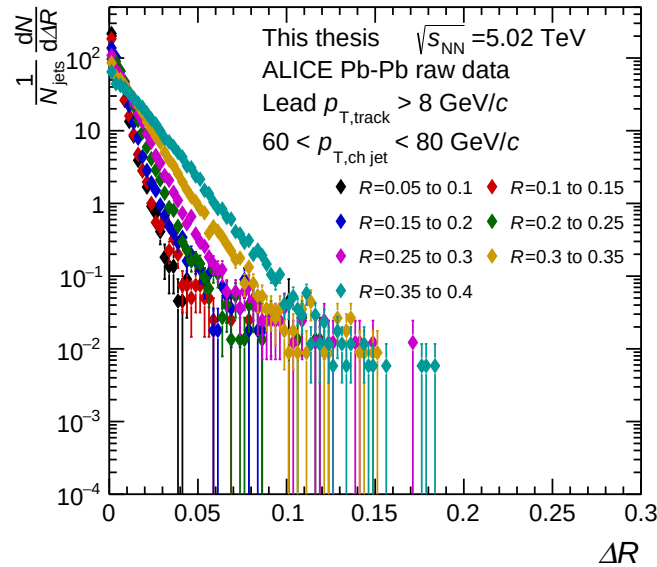


Figure 55: Distributions of the distance ΔR between the jet axis of matched jets with smaller and larger R_{jet} for radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE data from Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

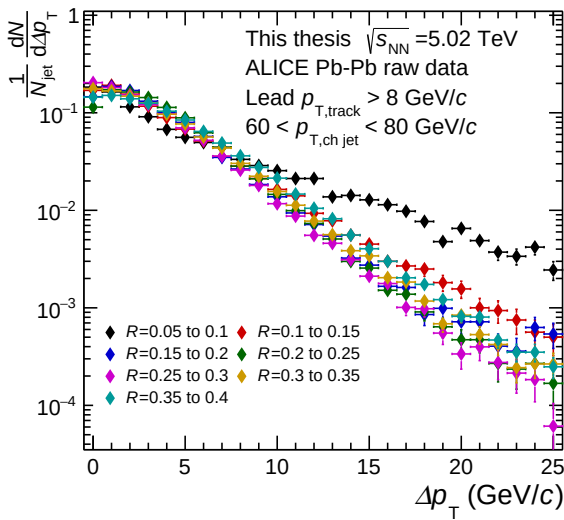
For each of the presented distributions, a selection on the p_T of the narrow jet, $60 \leq p_T < 80$ GeV/c, has been applied. In addition these distributions have been normalized to unity while

taking into account the bin width. For the examined phase space of R_{jet} , the distributions have a distinct peak at $\Delta R = 0$ and additionally the vast majority of the matched jets are in the region where $\Delta R < 0.05$. For larger jet radii, the ΔR distributions are broader while still maintaining that $\Delta R \leq R_{\text{jet}}$. This broadening of the ΔR is probably due to fluctuations of the underlying event, which are larger for the case of wider jets.

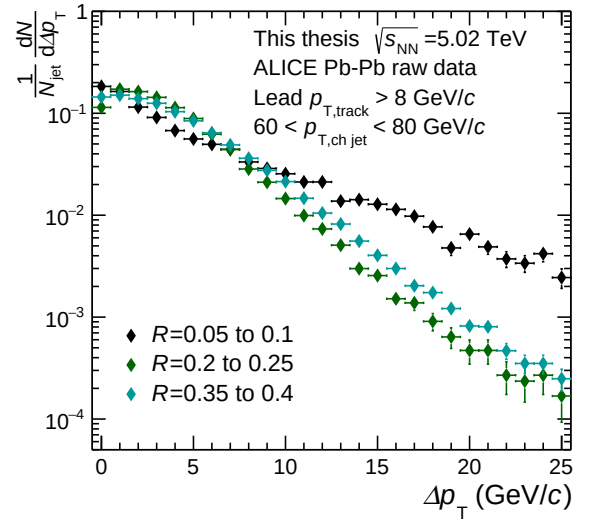
In addition, within the available statistical accuracy there is no secondary peak structure at large ΔR as was observed in the JEWEL model in Sec. 9.3.

11.3 JEFF distributions

The Δp_T measurement in ALICE Pb-Pb data before the application of corrections is presented in Fig. 56. A selection on the p_T , $60 \leq p_{T,\text{jet}} < 80$ GeV/c, of the narrow jet is applied in all of the distributions. The overview of all the analysed jet radius pairs is shown in Fig. 56a, while a selection of the narrowest, intermediate and widest jet radii is presented in Fig. 56b. These distributions are characterised by a steeply falling tail towards high values of Δp_T . However, the peak at $\Delta p_T = 0$ which was also evident in the case of pp collisions, is obscured in these distributions by a broader Gaussian-like shoulder. The breadth of the shoulder is increasing towards larger jet radii where the influence of the background fluctuations is stronger. Furthermore, with the exception of the most narrow jet pair, the distributions for the rest of the jet radial pairs lie very close to each other, obscuring the smooth transition as a function of the jet radius as it was observed in Sec. 10.3.



(a) Jet radial pair overview



(b) Selected radial pairs

Figure 56: Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE data from Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c. An overview of all the considered radial pairs is shown on the left panel while the distributions for $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.1$ (black), $R_{\text{jet}} = 0.2$ and $R_{\text{jet}} = 0.25$ (green), and $R_{\text{jet}} = 0.35$ and $R_{\text{jet}} = 0.4$ (cyan) are shown on the right.

The smearing of the distributions at small values of Δp_T is a consequence of the remaining background fluctuations from the underlying event. A similar effect was observed in the embedding

of JEWEL distributions in a thermal background (Sec. 9.5). In order to correct the measurement for the influence of these fluctuations an unfolding procedure is needed. Lastly, it should be noted that the jets in these distributions fulfill the requirement on the p_T of their leading hadron, $p_{T,\text{track}}^{\text{lead}} \geq 8 \text{ GeV}/c$.

11.4 Corrections

The measured energy flow distributions in ALICE Pb-Pb data which were presented in the previous section have to be corrected for the effect of the detector response and the fluctuations of the underlying event. This section is dedicated to the procedures which were used to qualify and benchmark these corrections. The analysis process of the embedded PYTHIA events follows the same steps for the jet matching and tagging that were presented in Sec. 10.4. The difference is that for the heavy-ion case the tagging is used to match jets at the generator truth ('particle') level and the hybrid level, i.e. the embedded detector level. The relation between the two levels in terms of jet momentum and energy flow for each jet radial pair is encoded in a 4-dimensional response matrix. Projections of the response matrix in two dimensions provide a clearer picture of the correspondence between the two levels for each observable.

The response matrix projection with respect to the jet p_T for narrow $R_{\text{jet}} = 0.05$, intermediate $R_{\text{jet}} = 0.2$ and wide jets $R_{\text{jet}} = 0.35$ are shown in Fig. 57. These maps have been normalized per row in order to reflect the probability distribution for the jet energy reconstruction at the hybrid level. A diagonal structure is present in all three of the presented radial cases however this correspondence gets increasingly smeared as the jet radius increases.

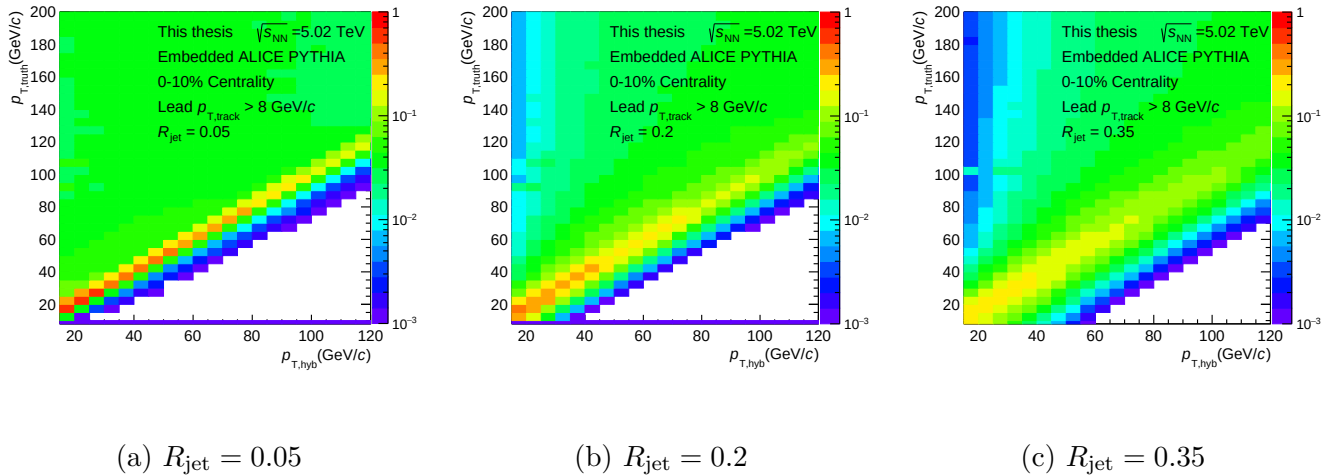


Figure 57: Projections of the response matrix for the jet p_T between truth and hybrid level in ALICE PYTHIA simulations embedded in ALICE Pb-Pb data for jets with radius $R_{\text{jet}} = 0.05$ (left), $R_{\text{jet}} = 0.2$ (middle) and $R_{\text{jet}} = 0.35$ (right).

For the jet energy flow observable, the response matrix projections for a selection on the truth level narrower jet in each pair of $60 \leq p_T < 80 \text{ GeV}/c$ are presented in Fig. 58. For the case of narrow and intermediate jet pairs a strong diagonal structure is seen, indicating a good correspondence between truth and hybrid level measurements. For the wider jets considered, this structure is missing and instead a reconstruction at $\Delta p_T \leq 5 \text{ GeV}/c$ at hybrid level is preferred regardless of the value at the generator level. The poor correspondence of the observable between

truth and reconstructed level for the energy flow is one of the reasons for the exclusion of the large jet radius cases from the rest of the analysis. Additional response matrix projection plots of the rest of the jet radial pairs for both p_T and Δp_T can be found in [Appendix B.1](#).

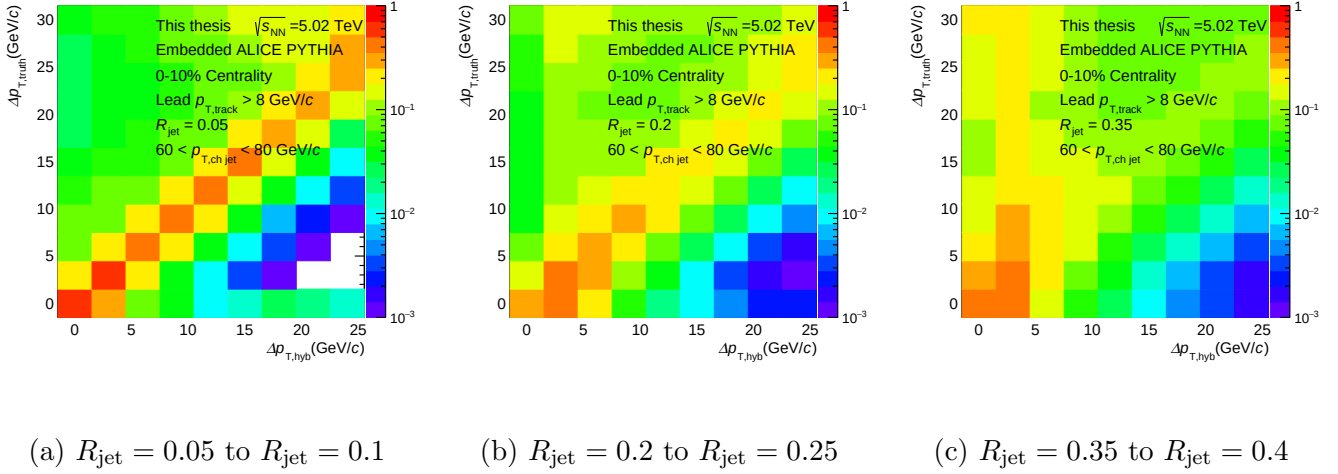


Figure 58: Projections of the response matrix for Δp_T between truth and hybrid level in ALICE PYTHIA simulations embedded in ALICE Pb-Pb data for matched jet pairs with radius $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (left), $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ (middle) and $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ (right). In all three panels a selection on the narrow jet's p_T at truth level, $60 \leq p_T < 80$ GeV/c, is applied.

One-dimensional distributions of jet energy response (Fig. 59a) and jet energy flow resolution (Fig. 59b) further illustrate the correspondence between truth and hybrid level information in terms of p_T and Δp_T , respectively. As discussed in Sec. 10.4 the jet energy bias and resolution can be read off from the position of the peak and the width of the energy recovery distribution respectively. A distinct asymmetry of the distributions towards negative values is present in these distributions with a clear dependence on the jet radius. For jets with radius $R_{\text{jet}} \geq 0.25$ the effect of background fluctuations dominates, and the distributions become very broad and more symmetric. The width of these distributions points towards a poor jet energy resolution. The significance of this effect is both complemented and enhanced from the lack of clear diagonal structure in the response matrix maps shown above. This observation is the second reason for the exclusion of the large radius cases from the next steps of the analysis. For the smaller jet radii, no jet energy bias is observed and the width of the distributions are comparable to the pp case. The influence of the uncorrelated background is more limited in the case of energy flow resolution. However, an asymmetry towards positive values is observed with a smooth dependence on the jet radius. Furthermore, the distributions are broader compared to the ones analysed in the pp case. The influence of the remaining background fluctuations is evident in the recovery distributions. The correspondence between the true and measured distribution encoded in the presented response matrix is used in the unfolding procedure of the experimental measurement.

The measured energy flow distributions in Pb-Pb data are corrected for the influence of background fluctuations as well as the detector response through the unfolding procedure. The unfolding method employed in this research is the iterative Bayesian inference method [215]. The free parameter in this technique is the number of iterations performed to reach the unfolded result. Prior to the application of this procedure to the measured distributions in the experimental data, its reliability and robustness have to be investigated through closure tests. In this analysis, the

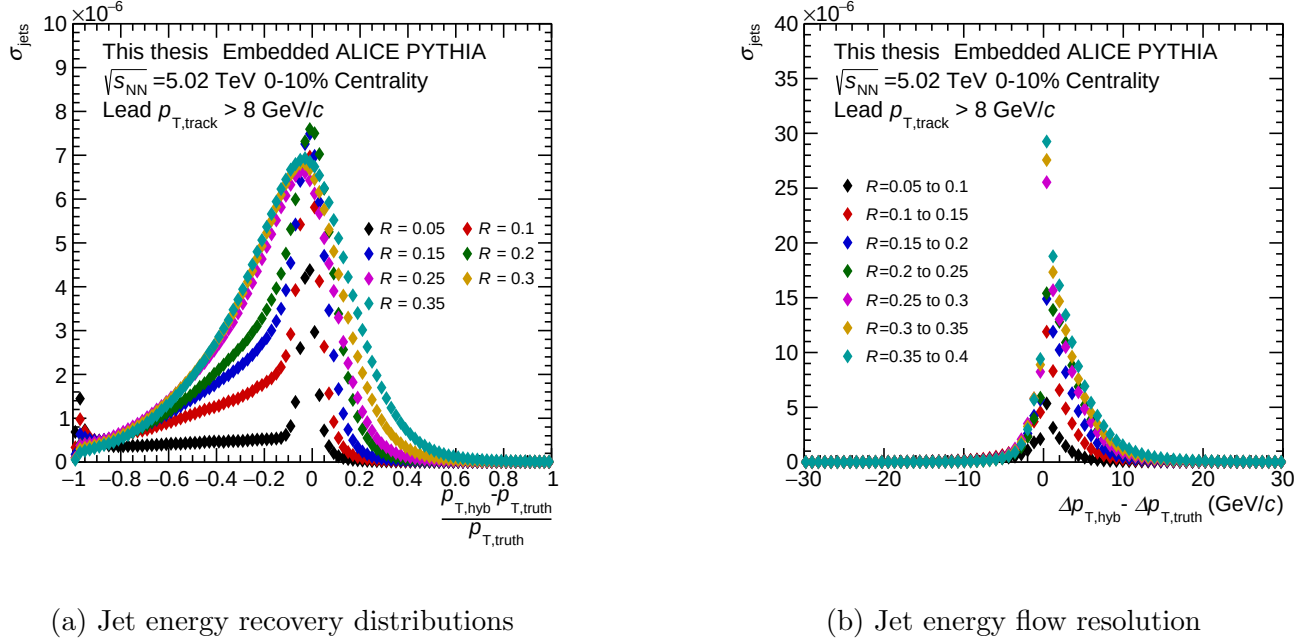


Figure 59: Jet energy resolution (left) and Δp_T resolution (right) plots for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE PYTHIA simulations embedded in ALICE Pb-Pb data. For both panels a selection on the jet p_T of the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

closure was examined at the truth as well as the reconstructed level. Separate simulated datasets were used to construct the response matrix and serve as input pseudodata for the unfolding procedure. The comparison of the unfolded result with the known truth level distributions for three jet radius values are presented in Fig. 60. The stability with respect to the number of iterations is also evaluated with these tests. Sufficient agreement between the two distributions is observed for the case of energy flow between $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$. For larger jet radii, a systematic deviation towards the tail of the distribution is observed.

The results of the closure tests at the reconstructed level where the input hybrid level distributions are compared with the refolded result of the unfolding procedure are shown in Fig. 61. This test investigates the reversibility of the unfolding procedure as well as its robustness with respect to the unfolding regularization parameter N_{iter} . For all of the examined jet radii, good closure is observed with little dependence on the number of unfolding iterations. Naturally, closure tests at both levels were performed for all of the examined jet radii, however for the sake of brevity only a selection of those jet radial pairs is presented in this chapter. The performance of the closure tests for the remaining jet radial pairs is presented in [Appendix B.2](#).

In summary, the correction measures and the performance of closure tests for the PYTHIA simulations embedded in ALICE Pb-Pb data exhibit sufficient quality for the jet radial pairs with $R_{\text{jet}} \leq 0.25$. The analysis of the larger jet radii was excluded from the remainder of this analysis. This decision was motivated by the poor performance of the closure tests at the truth level, the broad jet energy recovery distributions and the significant presence of non-diagonal contributions in the response matrix. For the smaller jet radii, the validation of the unfolding procedure with these indicators showed that it can be applied for the correction of the measurement in ALICE Pb-Pb data. The last ingredient towards a complete energy flow measurement in heavy-ion collisions is the calculation of the systematic uncertainties described in the following section.

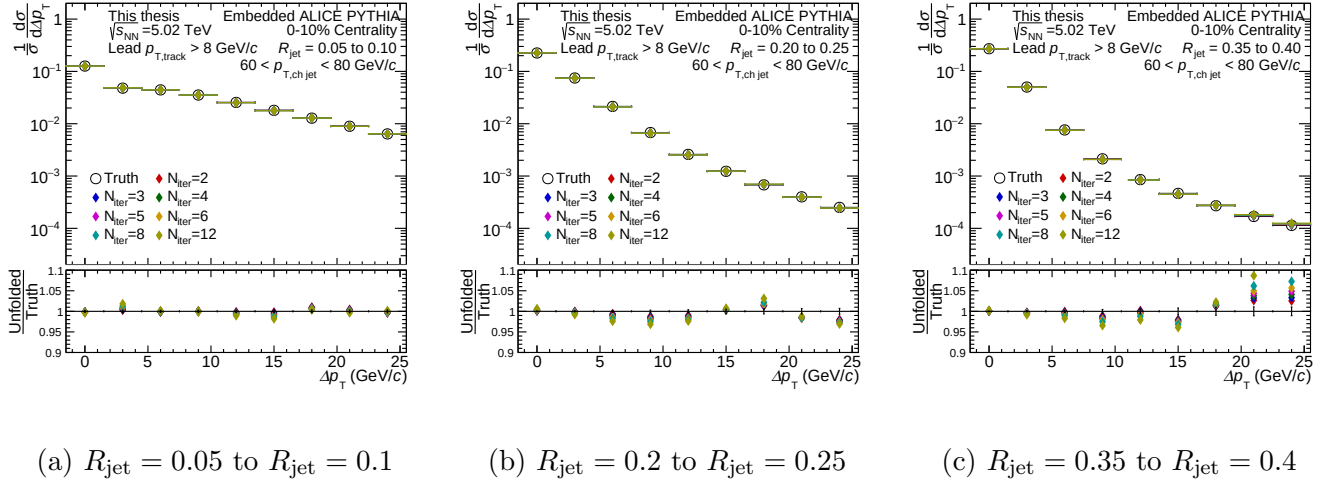


Figure 60: Closure test results at the truth level for Δp_T distributions for jet pairs with radius $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (left), $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ (middle) and $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ (right) in ALICE PYTHIA simulations embedded in ALICE Pb-Pb data. The bottom panels show the ratio between the unfolded and truth level distributions. In all three panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

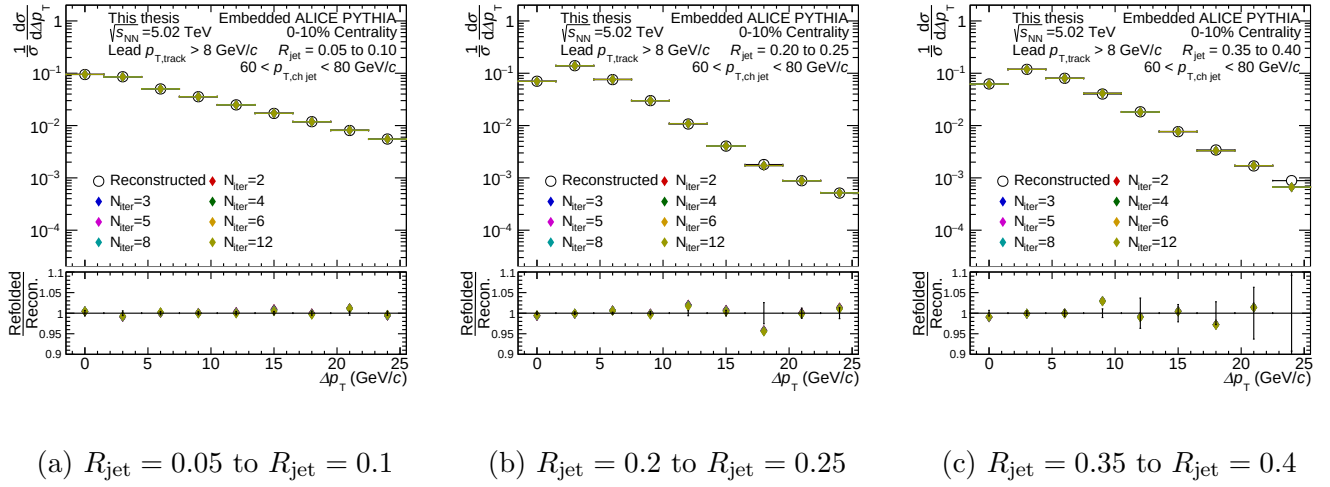


Figure 61: Results of closure tests at the reconstructed level for Δp_T distributions for jet pairs with radius $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (left), $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$ (middle) and $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$ (right) in ALICE PYTHIA simulations embedded in ALICE Pb-Pb data. The bottom panels show the ratio between the refolded and reconstructed level distributions. In all three panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

11.5 Sources of systematic uncertainty

The systematic uncertainties of the measurement are related to the experimental setup and the assumptions of the analysis method. The effect of the analysis choices and assumptions on the measured distribution are investigated through individual variations of those choices. For the measurement in Pb-Pb collisions these calculations were performed for the four jet radial pairs in the jet p_T range of $60 \leq p_T < 80$ GeV/c. The uncertainties are estimated based on the relative

ratio of the systematic variations on a bin-by-bin basis assuming a smooth dependence on Δp_T of the systematic uncertainty. The sources of systematic uncertainty investigated for the heavy-ion measurement are: the tracking efficiency, the unfolding procedure, the background subtraction method and the minimum p_T requirement on the jets' leading hadron.

The tracking efficiency in a heavy-ion measurement has been shown to be worse compared to the case of vacuum measurements due to the higher track density by 2%. This feature is implemented in the default response matrix through a random rejection of the embedded PYTHIA tracks at the detector level. In order to estimate the systematic uncertainty of the tracking efficiency, the track matching efficiency between ITS and TPC was studied in detail. The total uncertainty on the tracking efficiency is estimated to be 4%, with a mild dependence on the track momentum. A new simulation sample and response matrix with tracking efficiency reduced by this amount is produced and then used in the unfolding process of the measured distribution. The difference between the default unfolded measurement and the one with the modified response represents the corresponding systematic variation.

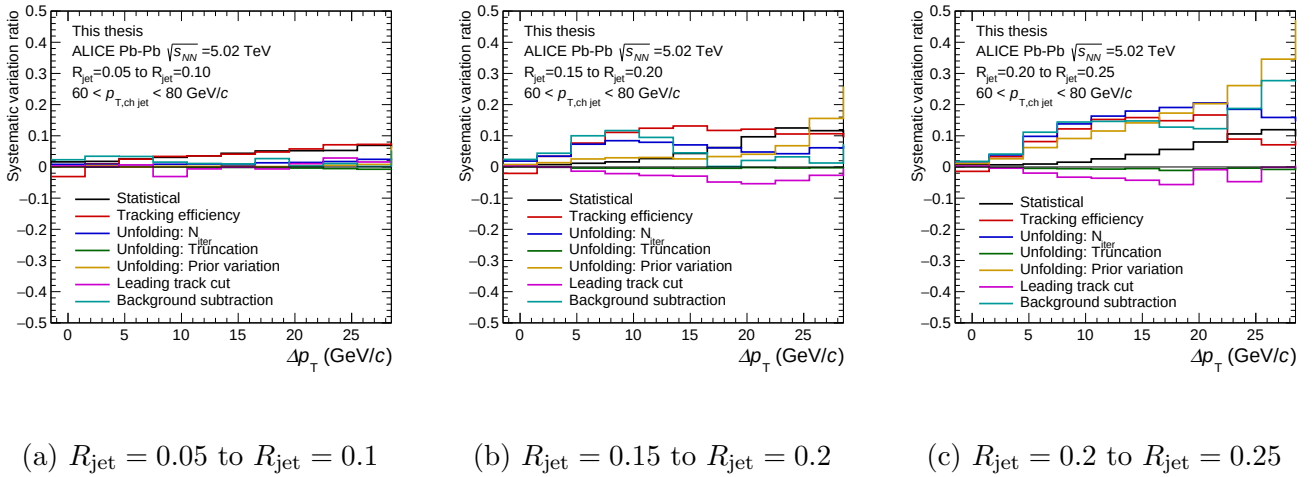


Figure 62: Overview of the relative systematic variation ratios for the smallest radial pair (left), intermediate (middle) and the largest radial pair (right) examined. A selection to the jet p_T , $60 \leq p_T < 80$ GeV/c, of the smaller jet radius has been applied. The statistical uncertainty of the default unfolded distribution is also plotted as a reference.

The systematic uncertainty related to the unfolding process is calculated through varying some of its key aspects. These are the number of unfolding iterations, N_{iter} , the detector threshold in jet momentum, and the shape of the truth level distribution. For N_{iter} , which is the regularization parameter of the Bayesian inference method, two unfolded results with higher and lower number of iterations compared to the default choice are produced. The average of the differences between these results and the default output is assigned as the systematic variation ratio. An increase of the momentum threshold at the detector level by 5 GeV/c in the determination of the response matrix is used to ascertain the systematic uncertainty of the momentum truncation. Furthermore a re-scaling of the prior distribution is used to estimate the systematic uncertainty related to the assumed shape of the truth level distribution. The default prior distribution is fitted with an exponential function and two functions with their slope modified by $\pm 5\%$ are produced. By scaling the default truth level distribution with the ratio of the modified over the original exponential fit function, two modified response matrices are produced. For each of these two matrices, the unfold-

ing procedure is repeated and the difference with the default unfolded measurement is calculated. The average of these differences between the unfolded results is assigned as the systematic variation. A total systematic uncertainty for the unfolding process is assigned as the quadratic sum of the uncertainties from each contribution divided by the number of contributions.

$R_{\text{jet}}^{\text{small}}$ to $R_{\text{jet}}^{\text{large}}$ Systematic Uncertainties	0.05 to 0.1	0.1 to 0.15	0.15 to 0.2	0.2 to 0.25
Tracking efficiency	1 – 7%	2 – 9%	2 – 11%	2 – 15%
Unfolding: N_{iter}	0 – 2%	2 – 3%	2 – 7%	2 – 18%
Unfolding: Prior variation	0 – 1%	0 – 2%	1 – 5%	2 – 22%
Unfolding: Jet p_T truncation	0 – 1%	0 – 1%	0 – 1%	0 – 1%
Background subtraction	1 – 3%	1 – 5%	2 – 10%	2 – 20%
Leading track p_T cut	0 – 2%	0 – 2%	0 – 4%	0 – 4%
Total	3 – 7%	4 – 9%	4 – 13%	3 – 28%

Table 5: Overview of the systematic uncertainties for the energy flow measurement in ALICE Pb-Pb data at the jet p_T range of $60 \leq p_T < 80$ GeV/c. The columns correspond to the four examined jet radial pairs between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.2$. The percentage range in each field indicates the lower and upper limits of the uncertainty in the reported Δp_T range.

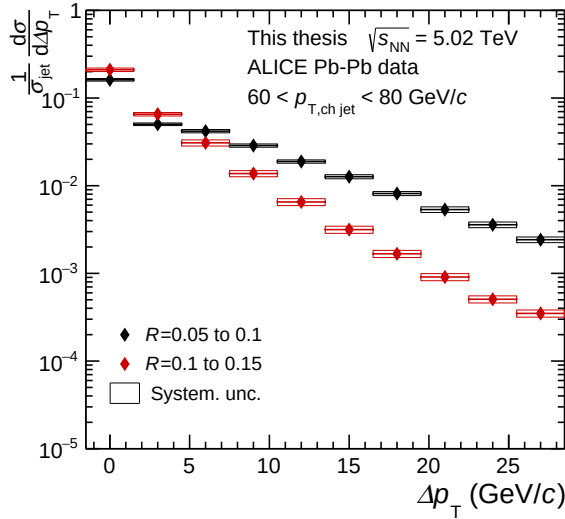
For the heavy-ion measurement, the analysis procedure includes a background subtraction method which operates on the constituent level. The systematic uncertainty related to this aspect is estimated through variations of the method’s free parameter ΔR_{max} . Varying this parameter may lead to over- and under-subtraction of the background. For each of the two variations, both a measurement on ALICE data and a simulation of embedded PYTHIA events is carried out. The data measurement for each choice of ΔR_{max} is unfolded using the response matrix that was calculated for a simulation sample with the same ΔR_{max} value. The average of the relative absolute differences between the default result of the unfolding and these two variation is used to estimate the systematic uncertainty related to the background subtraction.

Lastly, the energy flow measurement in the heavy-ion collisions includes a requirement on the minimum momentum of the leading hadron in the jet. This requirement however introduces a selection bias towards a hard fragmentation pattern. In order to estimate the effect of this requirement, the measurement was repeated in both experimental data and simulated events with a stricter cut of $p_{T,\text{lead}}^{\text{track}} \geq 10$ GeV/c. The relative difference between the unfolded result of this measurement and the default result is used to estimate the systematic uncertainty of this source. Like in the determination of the uncertainty related to background subtraction parameter, the variation of the p_T of the leading track was applied both on data and the simulated events.

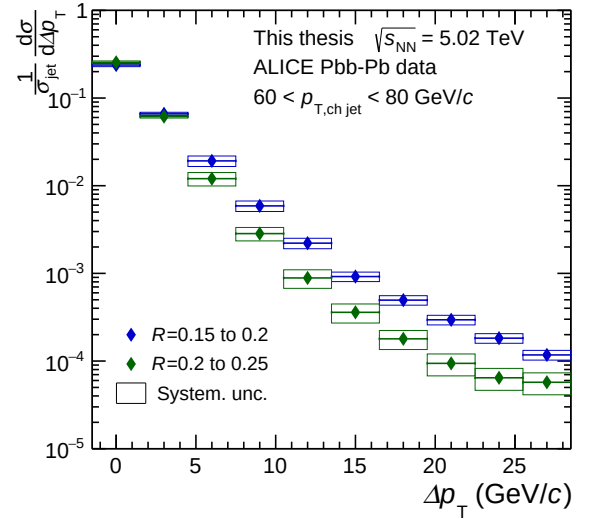
The total systematic uncertainty is calculated as the quadratic sum of the individual systematic uncertainties for each source. A selection of the systematic variation ratios which were used to estimate the uncertainties from each source is displayed in Fig. 62 for three jet radial pairs in the jet p_T range of $60 \leq p_T < 80$ GeV/c. The corresponding overview for the jet radial pair of $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ is shown in Appendix B.3. A comprehensive list of all of the examined cases is presented in the Tab. 5, where the columns represent the radial pairs and the ranges correspond to the dependence in Δp_T . The systematic uncertainties from the tracking efficiency and the influence of the background subtraction method are the most significant. Furthermore, the systematic uncertainty from all sources increases as the jet radius increases. This effect is expected since the influence of the underlying event and its fluctuations is stronger for larger jet radii.

11.6 ALICE Pb-Pb JEFF measurement

This section features the complete jet energy flow measurement in ALICE Pb-Pb data and in that way corresponds to the culmination of the analysis effort described in this chapter. The jet energy flow distributions for the jets with radius between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.25$ are shown in Fig. 63. A selection of $60 \leq p_T < 80$ GeV/c on the momentum of the narrow jet in each radial pair is applied. After the corrections, the distributions maintain the shape of steeply falling distribution with a distinct peak at $\Delta p_T = 0$ GeV/c. With the increase of the jet radius, the distributions become progressively steeper. The systematic uncertainties are larger for wider jets but still small enough for a meaningful comparison of different jet radii.



(a) Selection: $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.15$

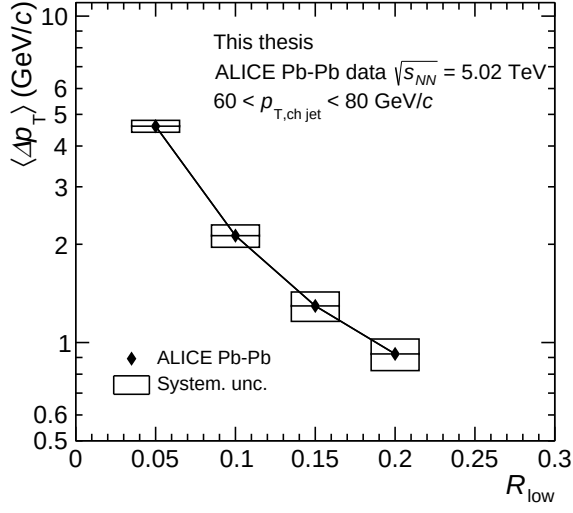


(b) Selection: $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.25$

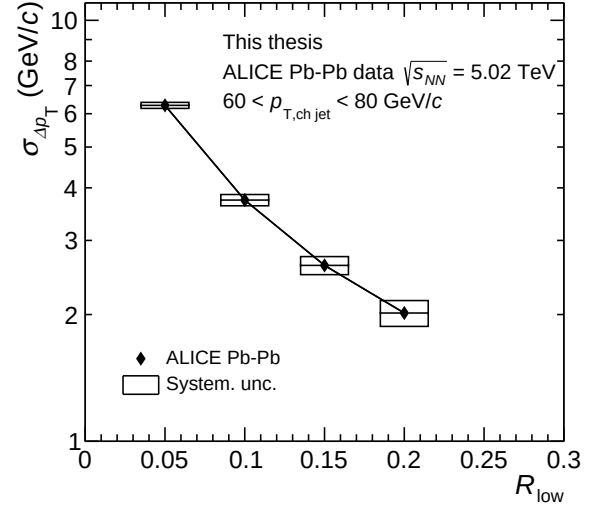
Figure 63: Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.15$ (left) and $R_{\text{jet}} = 0.15$ and $R_{\text{jet}} = 0.25$ (right) in ALICE data from Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

The evolution of the mean jet energy flow and its fluctuations as a function of the jet radius are shown in Fig. 64. A selection on the momentum of the narrow jet in each jet radial pair,

$60 \leq p_T < 80$ GeV/c, is applied. Both attributes show a decrease of the energy flow as the jet radius increases. Qualitatively, this behavior is in agreement with the JEWEL prediction for the case where the recoil effect is excluded (Fig. 36b). In the next chapter, these measurements are compared with the corresponding measurement in ALICE pp data and with the predictions of the JEWEL model.



(a) Mean energy flow



(b) Energy flow standard deviation

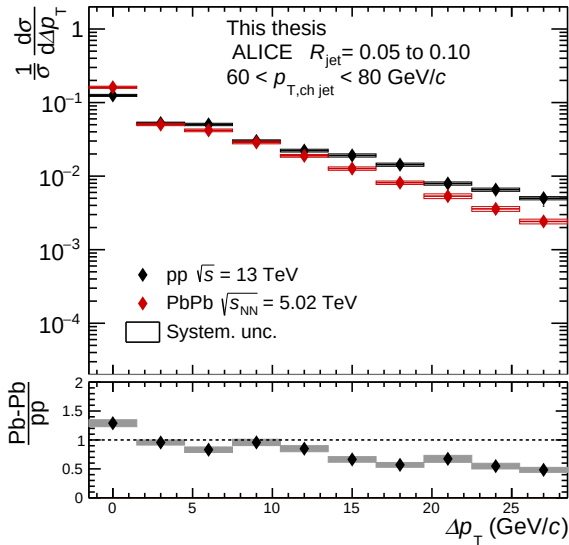
Figure 64: Measurement of the mean Δp_T (left) and its fluctuations (right) as a function of the R_{jet} in ALICE Pb-Pb data with a selection on the momentum of the narrow jet in each pair of $60 \leq p_T < 80$ GeV/c.

12 Comparison of JEFF Measurements

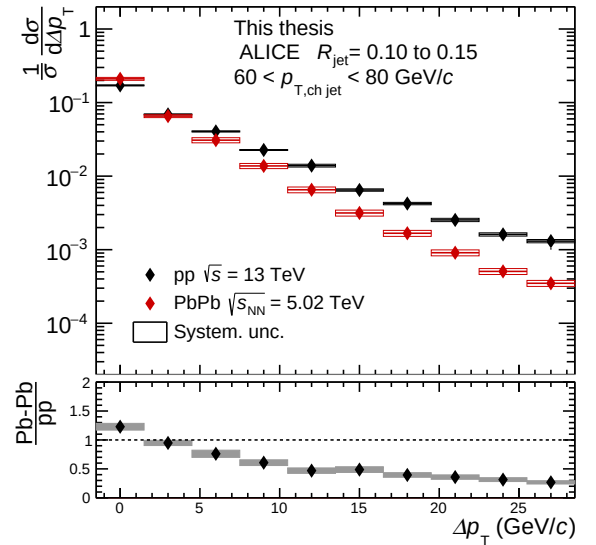
This chapter is dedicated to a comparison of the jet energy flow measurements performed with ALICE data. The measured Δp_T distributions as well as the mean energy flow and its fluctuations are compared between pp and Pb-Pb collisions in Sec. 12.1. In addition, each of these measurements is compared to model predictions from MC generators in Sec. 12.2. A more detailed interpretation of the results and their comparisons is presented in Ch. 13.

12.1 Comparison of experimental measurements

The comparison of Δp_T distributions measured in ALICE pp and Pb-Pb data for jets with radius between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.15$ as well as $R_{\text{jet}} = 0.15$ and $R_{\text{jet}} = 0.25$ are shown in Fig. 65 and 66 respectively. For each jet radial pair, a momentum selection, $60 \leq p_T < 80$ GeV/c, was applied to the jet with the smaller radius. The bottom panel in each figures shows the ratio of the distributions displayed in the top panel. The uncertainties on the ratio were calculated assuming that the measurements are uncorrelated.



(a) $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$



(b) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$

Figure 65: Comparison of measured Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.15$ in ALICE pp and Pb-Pb data. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

For each of the examined jet radii, the measured distribution in the case of heavy-ion collisions is steeper. This effect becomes more pronounced for jets with larger jet radius. A clear suppression is observed in Pb-Pb collisions for $\Delta p_T \geq 5$ GeV/c across all of the examined jet radii. It is important to note that each of the compared distributions has an integral of 1, i.e. that suppression at large Δp_T is balanced by an enhancement at small Δp_T .

The same observations are drawn from the comparison of the mean energy flow and its fluctuations, as indicated by the distributions' standard deviation. Fig. 67 shows the comparison of these attributes as function of jet radius for the two collision systems. In the range of jet radius

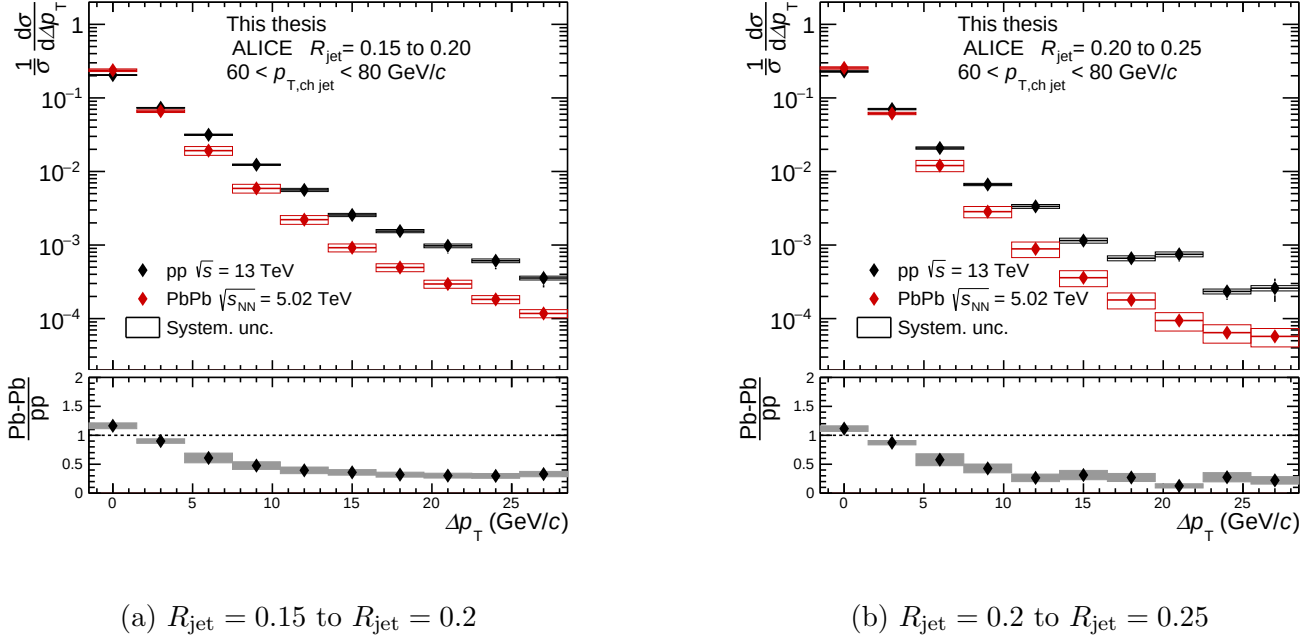


Figure 66: Comparison of measured Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.15$ and $R_{\text{jet}} = 0.25$ in ALICE pp and Pb-Pb data. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

where the comparison is available, the average energy flow in Pb-Pb collisions is smaller and the relative suppression increases for larger jets. This points to a jet narrowing effect in Pb-Pb collisions, where there is less energy flow at large angles compared to the pp case. It should be noted that the measurements in the two systems were performed at different collision energies. Further interpretation of the comparison and its caveats will be discussed in the next chapter.

12.2 Comparison with models

The jet energy flow measurements in ALICE pp and Pb-Pb data are compared with model predictions from MC generators for each of the analysed jet radial pairs. The model predictions include the same selection criteria in terms of jet momentum and pseudorapidity as the experimental measurements. For the case of Pb-Pb collisions, the requirement on the minimum momentum of the leading hadron in the jets used in data has been applied in the JEWEL predictions.

For the pp measurement, a comparison of the Δp_T with the predictions of PYTHIA8, HERWIG and JEWEL in vacuum is presented in Fig. 68. For each distribution, a selection on the momentum of the smaller jet in each radial pair, $60 \leq p_T < 80$ GeV/c, is applied. The bottom panel shows the ratios between each model prediction and data with the systematic and statistical uncertainties of the measurement drawn, centered at unity. For all of the jet radii, both PYTHIA8 and HERWIG describe the measurement in pp collisions and exhibit excellent agreement. The JEWEL generator predicts a steeply falling distribution like in data however it disagrees considerably with the measurement in the examined Δp_T range. Specifically, the JEWEL model shows a smaller number of cases at $\Delta p_T = 0$ and a flatter tail in larger Δp_T . The two characteristics are likely correlated since the presented distributions are normalized to an integral of unity.

Fig. 69 shows the comparison of the mean energy flow and its fluctuations measured with the

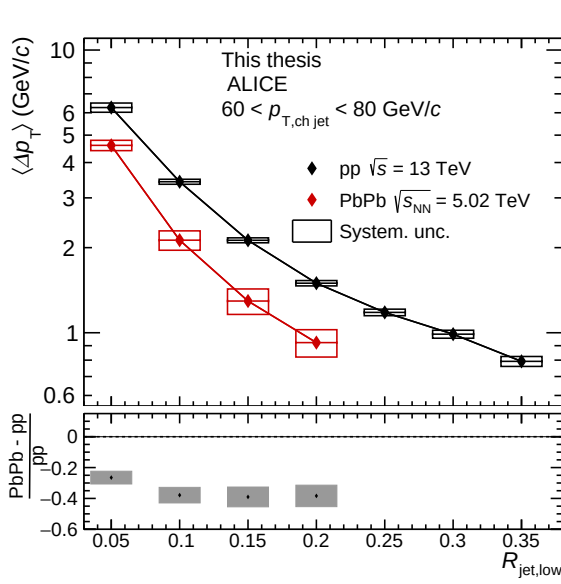
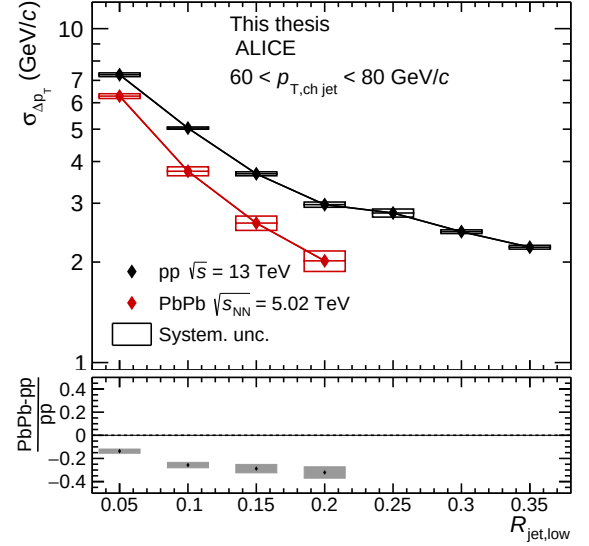
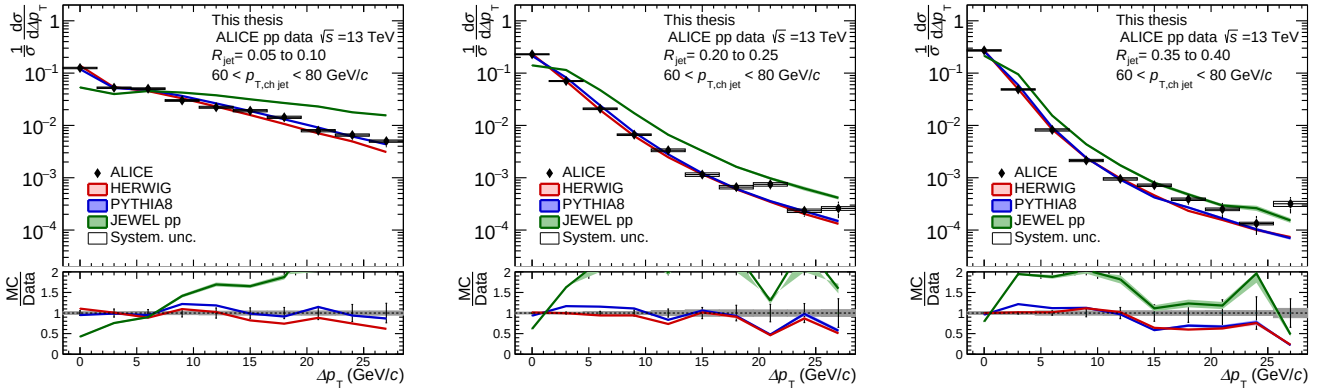

 (a) Mean energy flow as a function of R_{jet} .

 (b) Standard deviation of the energy flow distribution as a function of R_{jet} .

 Figure 67: Comparison of mean energy flow (left) and its standard deviation (right) for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.25$ in ALICE pp and Pb-Pb data. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

 (a) $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$

 (b) $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$

 (c) $R_{\text{jet}} = 0.35$ to $R_{\text{jet}} = 0.4$

 Figure 68: Comparison of measured Δp_T distributions in ALICE pp data at $\sqrt{s} = 13$ TeV with model predictions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

ALICE pp data for the same set of model predictions. All three models qualitatively describe the decrease of these observables as the jet radius increases. However as expected from the above observations, the JEWEL model overestimates both the mean energy flow and its standard deviation throughout the examined range of jet radii. Model comparisons of the ALICE pp measurement for the rest of the jet radial pairs and for the jet population with momentum $40 \leq p_T < 60$ GeV/c

can be found in [Appendix A.4](#).

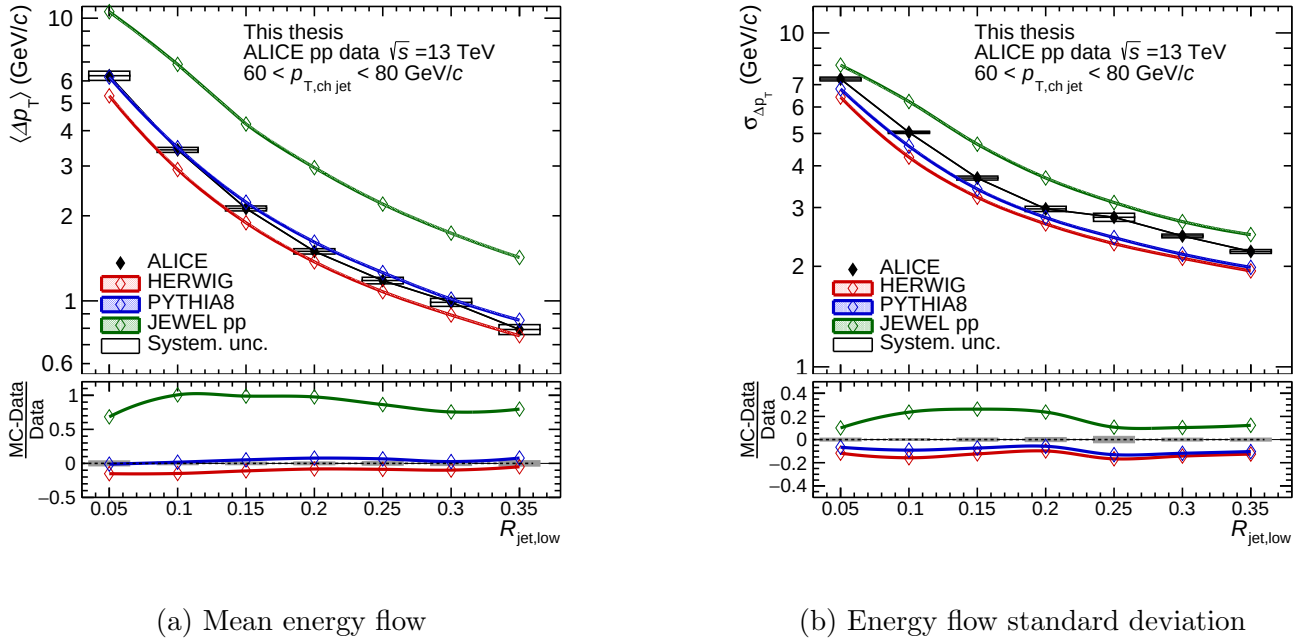


Figure 69: Comparison of mean energy flow (left) and its standard deviation (right) for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE pp data at $\sqrt{s} = 13$ TeV with model predictions. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

The experimental measurement of jet energy flow in Pb-Pb collisions is compared with calculations using the JEWEL event generator with and without recoils in Fig. 70. For each of the presented distributions a selection on the momentum of the smaller jet in each pair of $60 \leq p_T < 80$ GeV/c, is applied. The corresponding plot for the jet radial pair of $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ is featured in [Appendix B.4](#).

As expected from the studies in Ch. 9, JEWEL with and without recoil gives similar predictions for the energy flow in the case of small jet radii. Similarly to the pp case, the JEWEL model underestimates the measurement in the first bin, especially in the recoil-inclusive case. This feature is then compensated by an overestimation of the measurement in the rest of the bins.

Fig. 71 shows the comparison of the ALICE measurement in Pb-Pb with the two JEWEL AA predictions regarding the dependence of mean energy flow and its fluctuations on the size of the jet. In both of these indicators the JEWEL predictions significantly overestimate the experimental measurement while the two modes show a clear difference in their predictions for larger jet radii. The relative difference between the experimental result and the model prediction is constant as a function of the jet radius for the case where the recoil effect is ignored in the event simulation. When the information on the medium recoil partons is maintained, the model predicts an increasing overestimation of both energy flow indicators as the jet radius increases.

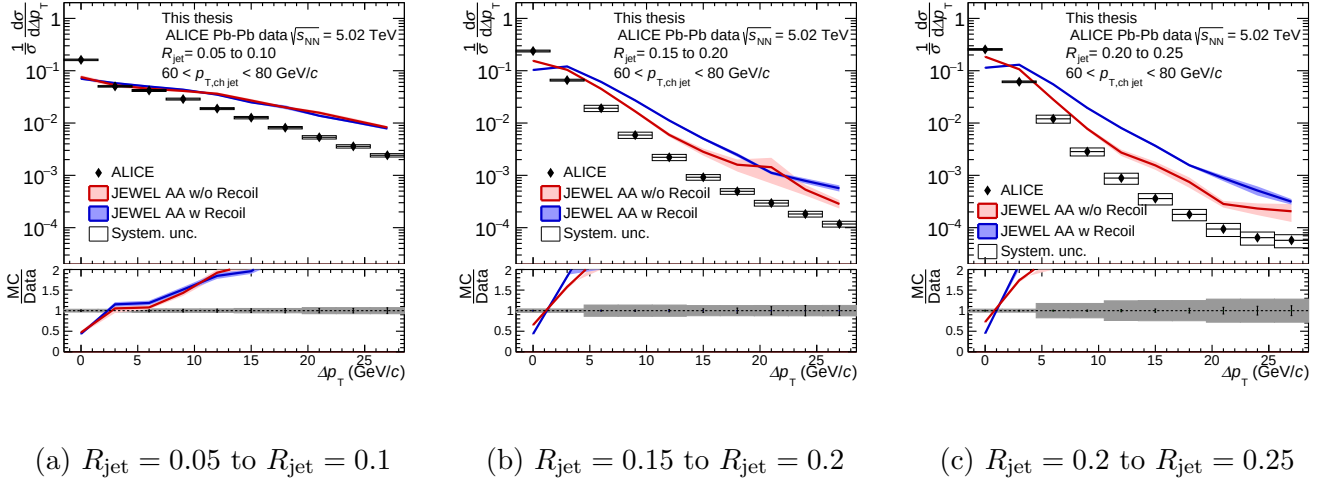


Figure 70: Comparison of measured Δp_T distributions in ALICE Pb-Pb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with model predictions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.25$. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

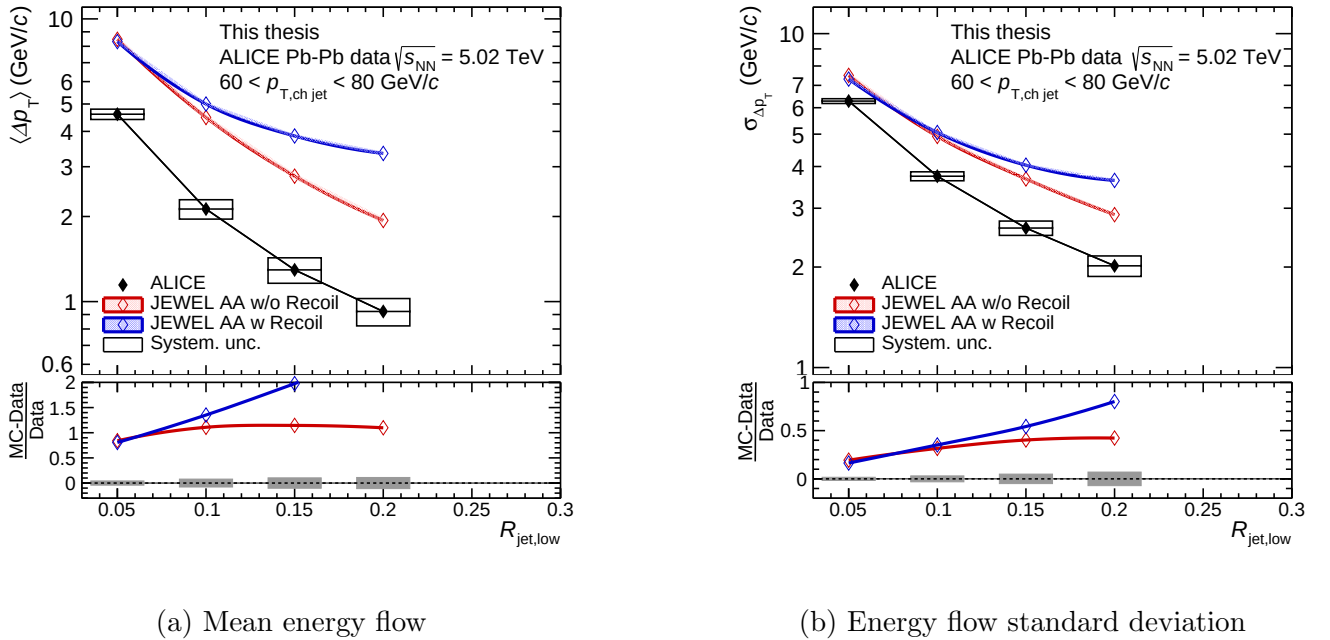


Figure 71: Comparison of mean energy flow (left) and its standard deviation (right) for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.25$ in ALICE Pb-Pb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with model predictions. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

13 Discussion

This chapter is dedicated to an in-depth comparison and interpretation of the jet energy flow measurements and their agreement with model predictions (see Sec. 13.1). Sec. 13.2 addresses how these results agree and complement previous jet quenching measurements. Lastly, secondary conclusions and supplementary investigations of the main results are presented in Sec. 13.3.

13.1 Discussion of JEFF measurement

To facilitate the interpretation of the jet energy flow measurement it is useful to revisit the main observations for the results introduced in Sec. 12.1 and 12.2. The jet energy flow measurement with the ALICE data in pp collisions serves as the reference measurement for the study of jet quenching in heavy-ion collisions. The majority of the jet energy is concentrated at a short distance from the jet axis. According to this expectation, the mean energy flow is decreasing as the jet radius increases. This monotonic decrease of the energy flow can be seen in Fig. 53. In the examined range of jet momentum, a smooth dependence of jet energy flow on p_T is observed. The measured Δp_T distributions for all the jet radii are very well described by the PYTHIA8 and HERWIG event generators, see Fig. 68 and 69. On the other hand, while the JEWEL model prediction is a steeply falling distribution, the model does not describe the measurement. Specifically, JEWEL underestimates the cases with no energy flow ($\Delta p_T = 0$). Due to the normalization of the distributions to an integral of unity, the discrepancy in the first bin is compensated by an overestimation at the tail of the distribution with respect to the experimental measurement.

The agreement of the experimental measurement with both PYTHIA8 and HERWIG simulations confirms the reliability of the generators but also reveals that the observable is not sensitive to the different implementations of the underlying physics mechanisms by the two models. The main differences between the generators, which are relevant for this discussion, are related to the modelling of the parton shower and the hadronization scheme. Specifically, HERWIG uses an angular-ordered parton shower that prioritizes color coherence, ensuring a more accurate description of soft gluon emissions. On the other hand, PYTHIA8 uses a transverse momentum-ordered shower emphasizing the direct link between the hard scattering process and subsequent emissions. The agreement of the measurement with both models shows that the observable has reduced sensitivity to the parton shower implementations. PYTHIA8 and HERWIG also differ in the implementation of hadronization mechanisms. HERWIG's cluster model [228], which forms color singlet clusters before hadronization, is particularly effective in scenarios involving baryon production. PYTHIA8 uses the Lund string model [229, 230] which emphasizes color conservation by stretching a color string between partons. The description of the measurement by both models shows that the observable is robust with respect to the hadronization scheme employed. An alternative interpretation of the model agreement is that the fine-tuning of PYTHIA8 and HERWIG to describe other experimental measurements, masks the sensitivity of the jet energy flow observable to these physics mechanisms.

The measurement of jet energy flow with the ALICE Pb-Pb data is more restricted in the range of both jet radius and momentum. In the examined phase space, a decreasing energy flow as a function of the jet radius is observed similarly to the vacuum case (Fig. 64). The Δp_T distributions are steeply falling with an increasing slope for larger jet radii (Fig. 63). These measurements are compared with two predictions of the JEWEL model, with or without recoils. In the recoil-inclusive mode, the information of the medium constituents that interacted with the jet partons is propagated to the event record. In this mode, the momentum contribution from the

medium must be subtracted. On the other hand, in the recoil-exclusive mode, the energy loss of the jet constituents due to medium interactions is still simulated, but the recoil particles are not tracked afterward. These two operational modes can be considered as opposite limiting cases for the treatment of medium response in jet measurements. For the jet energy flow measurement, the two recoil options provide distinct predictions for the Δp_T distributions. Both simulation options fail to describe the measurement as they underestimate the jet population in the first bin and compensate by an overestimation in the tail of the distribution. Specifically, the recoil-inclusive prediction shows increasing disagreement with the data for larger jets (Fig. 70 and 71).

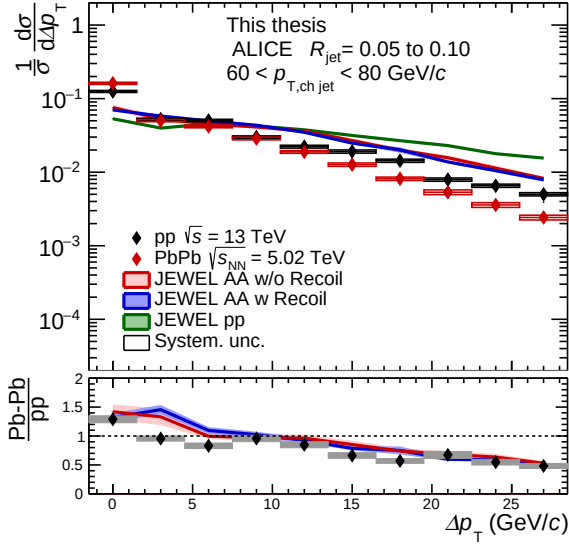
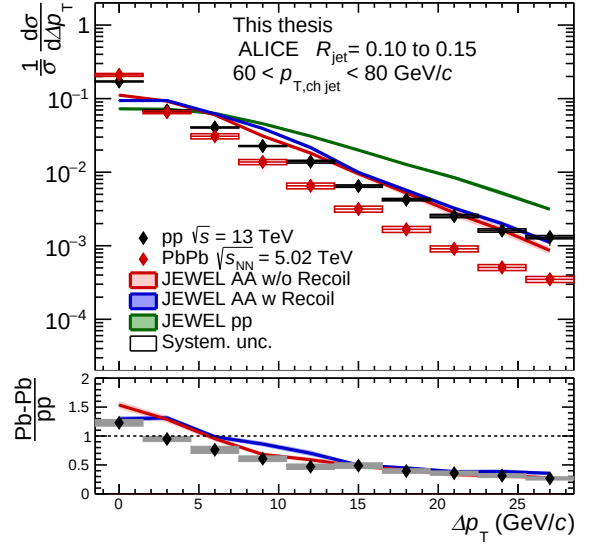
(a) $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (b) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$

Figure 72: Comparison of measured Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.15$ in ALICE pp and Pb-Pb data. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

The jet energy flow observable is designed to study the effects of jet quenching by means of comparison between the pp and Pb-Pb measurements. The comparisons of the Δp_T distributions are shown in Fig. 65 and 66. In addition, the comparison of the mean energy flow and its fluctuations as function of R_{jet} is presented in Fig. 67. The comparison of the Δp_T distributions shows a suppression in Pb-Pb collisions towards large Δp_T . This suppression is stronger for larger jets in heavy-ion collisions. The mean energy flow and its fluctuations as a function of the jet radius are more steeply decreasing in the Pb-Pb measurement compared to the vacuum case. Specifically, the mean energy flow in Pb-Pb collisions is approximately 40% smaller compared to the pp measurement for $R_{\text{jet}} \geq 0.1$. This comparison shows that the energy flow profile in heavy-ion collisions is narrower. Evidence of this characteristic have also been identified in previous jet quenching measurements, as it will be explained in the next section. While the energy flow measurements in pp and Pb-Pb collisions were carried out at different collision energies, and using an additional jet selection to suppress background in Pb-Pb collisions, these differences are not expected to impact the qualitative conclusions in the following paragraphs. This expectation is confirmed by investigations of these effects in MC studies which are discussed in more detail in Sec. 13.3.

As it was shown in Fig. 68 and 70 the JEWEL model disagrees with the experimental measure-

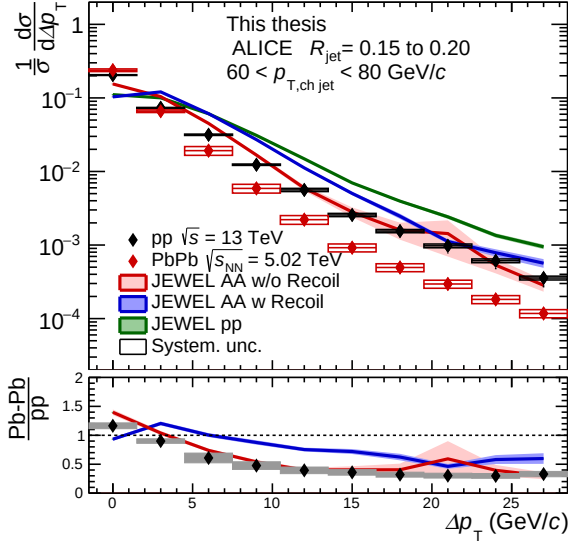
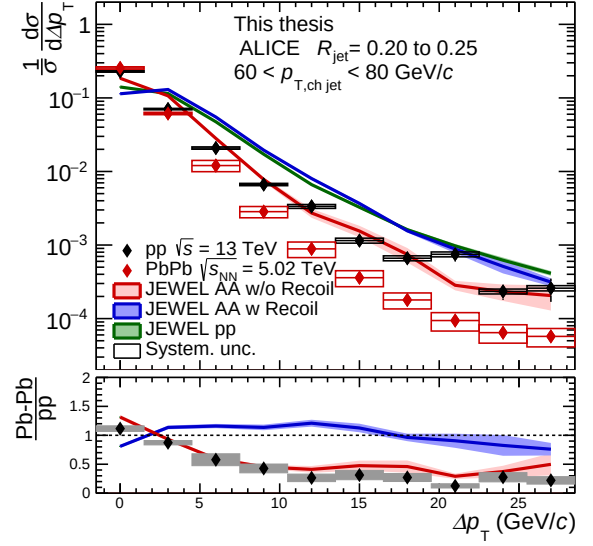
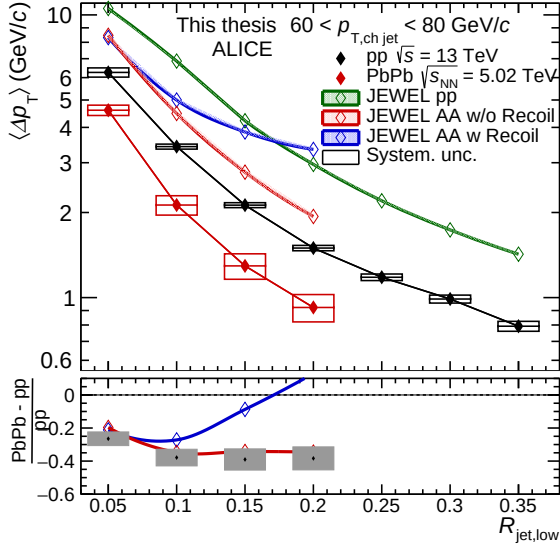
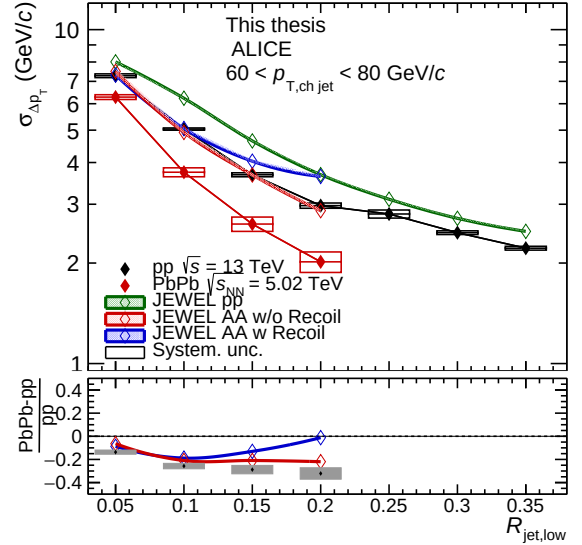
(a) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.20$ (b) $R_{\text{jet}} = 0.20$ to $R_{\text{jet}} = 0.25$

Figure 73: Comparison of measured Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.15$ and $R_{\text{jet}} = 0.25$ in ALICE pp and Pb-Pb data. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.



(a) Mean energy flow



(b) Energy flow standard deviation

Figure 74: Comparison of mean energy flow (left) and its standard deviation (right) for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.25$ in ALICE pp and Pb-Pb data. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

ments for both pp and Pb-Pb collisions. However, the relative modification of jet energy flow in heavy-ion collisions is captured by the JEWEL model in the recoil-exclusive case, as it can be seen

in the distribution ratios presented in Fig. 72 and 73. In the jet radius range ($R_{\text{jet}} \geq 0.15$), where the recoil effect becomes significant, the recoil-inclusive case underestimates the level of suppression observed in the experimental measurements. Fig. 74 shows that the R_{jet} –dependence of mean energy flow and its standard deviation is well described by the relative difference of the JEWEL prediction in the pp and AA w/o recoil case. The inclusion of recoil effects leads to an underestimation of the jet narrowing effect. Furthermore, the largest deviation between MC prediction and measurement is seen for large jets with $R_{\text{jet}} \geq 0.2$ where JEWEL expects an enhancement. The success of the recoil-exclusive mode, which neglects the medium response, is surprising but has also been observed in other observables like the R_{AA} double ratio [197]. On the other hand, jet shape measurements are better described by models that include medium response [173]. In those cases the recoil-inclusive mode provides better agreement. Additional work on the JEWEL model is needed in order to clarify whether the discrepancies can be resolved with model tuning to describe recent experimental results or whether the implemented fundamental physical mechanisms have to be revisited. An extension of the current measurement in heavy-ion collisions to larger radii would explore the redistribution of medium-induced radiation at larger angles. This requires an improved treatment or further suppression of background fluctuations in the measurement.

13.2 Complementarity with other measurements

The Δp_T observable is designed to study the phenomenon of jet quenching as a function of the jet radius. Particularly it is sensitive to the modification of the jet angular structure. As such, it is complementary to the measurements of the nuclear modification factor, R_{AA} , as a function of the jet radius which have been performed by the ALICE [197], CMS [198] and the ATLAS [184, 206] collaborations. These measurements show that the R_{AA} double ratio is consistent with unity in an extended range of jet radii $0.2 \leq R_{\text{jet}} \leq 1$, with the ALICE measurement showing a hint of suppression for the $R_{AA}^{R=0.6}/R_{AA}^{R=0.2}$ measurement (Fig. 75b). A tension between these measurements and the earliest R_{CP} measurement from ATLAS [206] has sparked a lot of discussion within the scientific community, however the many differences in the jet populations examined in the two cases may explain this disagreement. In this discussion, the energy flow measurement contributes with the exploration of the jet radius dependence in smaller jets $0.05 \leq R_{\text{jet}} \leq 0.25$, showing a clear narrowing of the intra-jet energy flow. Furthermore, the experimental measurements of the nuclear modification factor double ratio are bracketed by the predictions of the JEWEL model for the two recoil treatments. On the contrary, JEWEL disagrees with the Δp_T measurement in both pp and Pb-Pb collisions but manages to capture the relative modification in the recoil-exclusive case. The description of the measurement by the JEWEL recoil-exclusive mode is also evident in the double R_{AA} ratio measurement by ALICE as it is shown in Fig. 75.

Another observable is the differential jet shape which measures the radial distribution of transverse momentum inside the jet,

$$\rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in [r_a, r_b]} p_T^{\text{track}}}{p_T^{\text{jet}}} \quad (21)$$

, by dividing the cone in circular annuli of width $\delta r = 0.05$ with inner and outer radius, $r_a = r - \delta r/2$ and $r_b = r + \delta r/2$ respectively for each annulus. Measurements of the jet shape by the CMS collaboration [173] as well as its modification in Pb-Pb collisions as a function of centrality are shown in Fig. 76. For central Pb-Pb collisions, the jet shape ratio is suppressed at small distances $r \leq 0.2$ followed by an enhancement of the momentum flow at large angles. Both of these effects

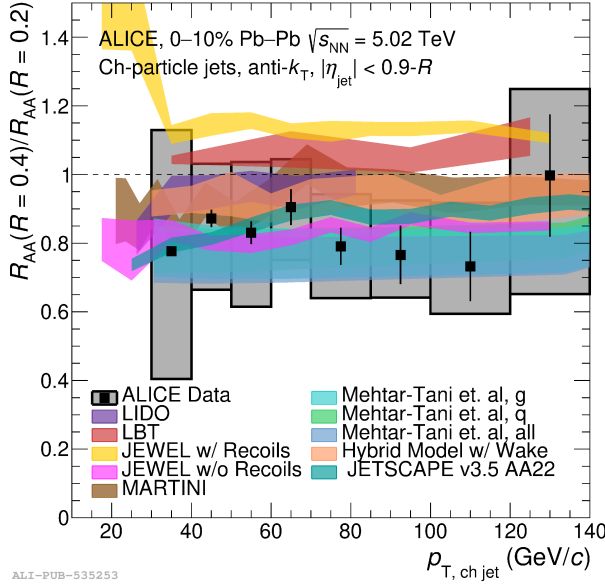
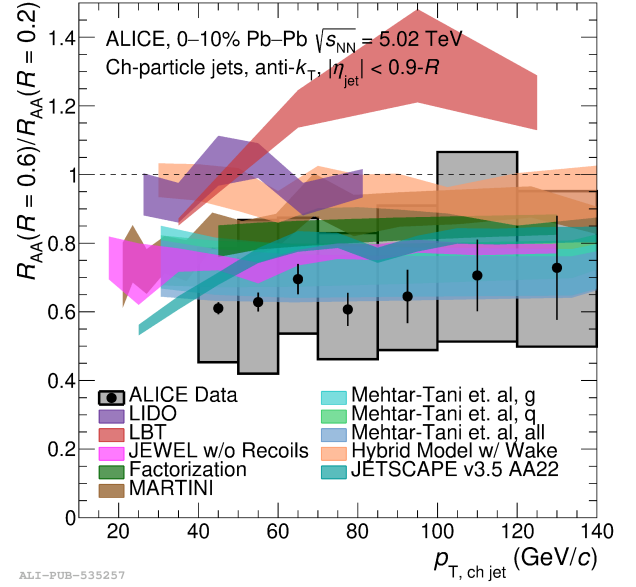
(a) Double ratio of $R_{AA}^{R=0.4}/R_{AA}^{R=0.2}$ (b) Double ratio of $R_{AA}^{R=0.6}/R_{AA}^{R=0.2}$

Figure 75: Measurement of the double ratio of R_{AA} as a function of the jet radius by the ALICE collaboration. Multiple model comparisons are also featured. The JEWEL prediction with recoils is out of scale for the $R_{AA}^{R=0.6}/R_{AA}^{R=0.2}$ comparison (right) [197].

become milder in the transition from central to more peripheral collisions. These observations show that the jet momentum profile is narrower in heavy-ion collisions while some of the energy is re-distributed at large distances from the jet axis. Follow-up studies of the jet momentum profile by CMS [169] showed that the energy redistribution at the large angles of the jet is primarily due to low momentum particles. The jet shape observable corresponds to the mean of the energy flow measure used in this thesis, in the case that the jet axes of the radial pair are perfectly aligned. The Δp_T distributions are in addition sensitive to the event-by-event fluctuations of the jet energy flow which are not captured by the mean energy flow that is characterised by $\rho(r)$. In that regard, the observation of suppressed mean energy flow in small jet radii reported in this dissertation agrees with the jet shape and profile measurement although there are significant differences in the examined range of jet momentum. Unfortunately, the redistribution of energy at large angles discovered in the jet shapes measurements cannot be confirmed due to the limited measurement of Δp_T in the Pb-Pb collisions. In terms of model agreement, the modification of the jet profile in heavy-ion collisions is better described by the recoil-inclusive mode [156]. The contrary agreement of the energy flow modification with the recoil-exclusive mode of JEWEL warrants further investigation.

Another observable which is related to the jet energy flow explored in this work is the study of subjet fragmentation functions through the measurement of the momentum fraction,

$$z_r = \frac{p_T^{subjet}}{p_T^{jet}}. \quad (22)$$

This observable explores the energy distribution within the jet and shares definition similarities with the Δp_T measurement. For that measurement, the constituents of a jet with a given radius R_{jet} are re-clustered into smaller subjets with radius $r < R_{jet}$. A z_r measurement by the ALICE

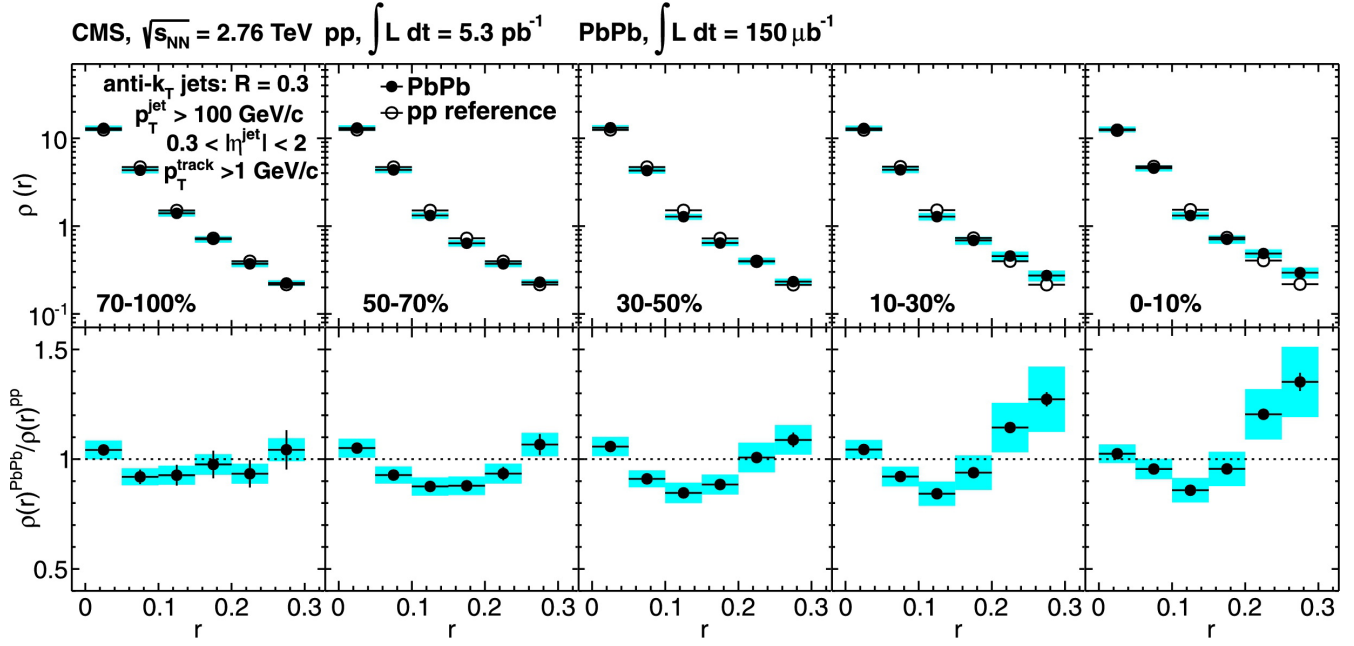


Figure 76: Measurement of jet shapes in Pb-Pb collisions by the CMS collaborations for jets with $p_T > 100$ GeV/c in five centrality bins. The bottom panels show the modification of the jet shapes with respect to the pp reference measurement [173].

collaboration on jets with $R_{\text{jet}} = 0.4$ reconstructing subjets with $r = 0.1$ and $r = 0.2$ was performed in pp and Pb-Pb collisions [166]. The study found that for the leading subjets, the distributions for both subjet radii are consistent with no modification between vacuum and heavy-ion collisions. However, a hardening trend of the distribution is evident in the Pb-Pb case which reverses as the momentum fraction approaches unity. In addition, this effect appears to be stronger for the smaller subjets of $r = 0.1$. The definitions of z_r and Δp_T have obvious similarities. However, in the case of z_r , since subjets are re-clustered by the jet constituents, the matching between small and large jets is implicit. Furthermore due to this definition, the jet population explored in the z_r measurement matches to the subset of jets for which $\Delta p_T = 0$ in the energy flow measurement. Also, the reported z_r measurement uses a larger increase of the jet cone ($\delta R = R - r$) compared to the energy flow results presented in this dissertation ($\delta R = R_{\text{step}} = 0.05$). The larger radial increment may be necessary for the inclusive z_r measurement. In that way multiple spatial configurations of the subjets within the jet cone are explored. This difference, as well as the broad kinematic range explored by the Δp_T distributions means that the two measurements are complementary in their investigations.

Fig. 77 shows the ratio of the subjet momentum fractions for $r = 0.1$ and $r = 0.2$ in Pb-Pb collisions. This ratio probes the r -dependence of the z_r measurement. The JEWEL predictions featured in the same figure show that the two recoil modes fail to describe the data but instead bracket the experimental measurement. In particular in the high z_r region which corresponds to the low Δp_T phase space, the JEWEL model predicts a narrower fragmentation profile compared to the measurement. This observation moves in the opposite direction compared to the broader Δp_T distribution the JEWEL model seen in Fig. 70. On the other hand, the decrease of the mean energy flow for larger jet radii agrees with the enhancement of the z_r distribution for $r = 0.1$ compared to $r = 0.2$ in most of the momentum fraction phase space.

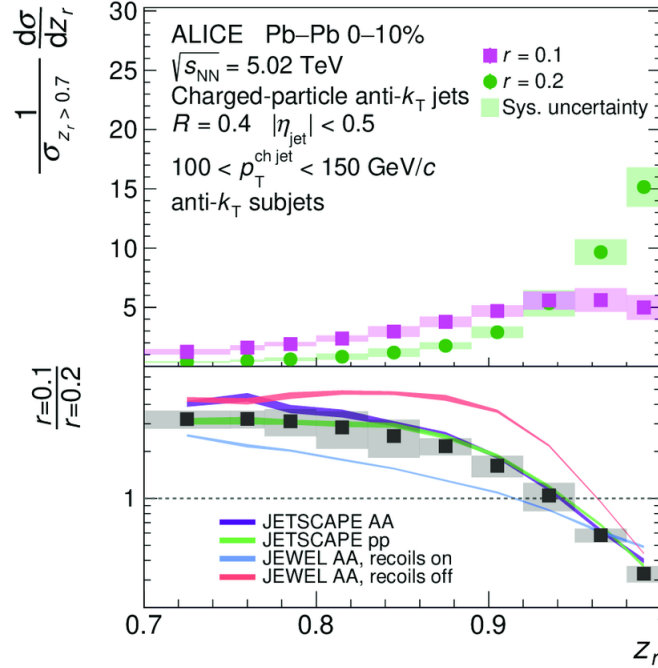


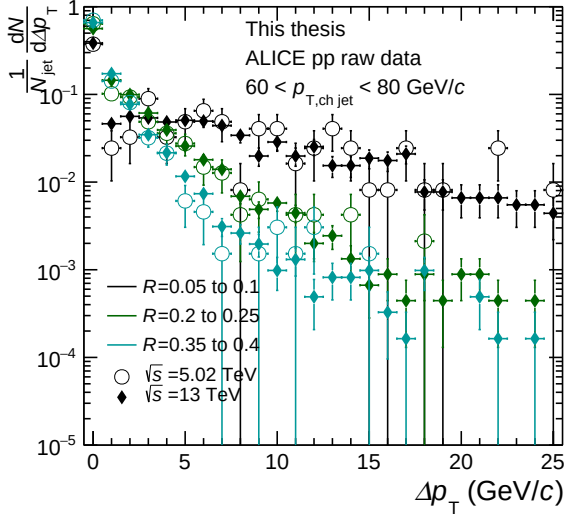
Figure 77: Measurement of the subjet momentum fraction in Pb-Pb collisions by the ALICE collaboration for jets with $100 < p_T < 150$ GeV/c. The bottom panel show the ratio of the two distributions which probe the r -dependence of the z_r observable [166].

13.3 Further considerations

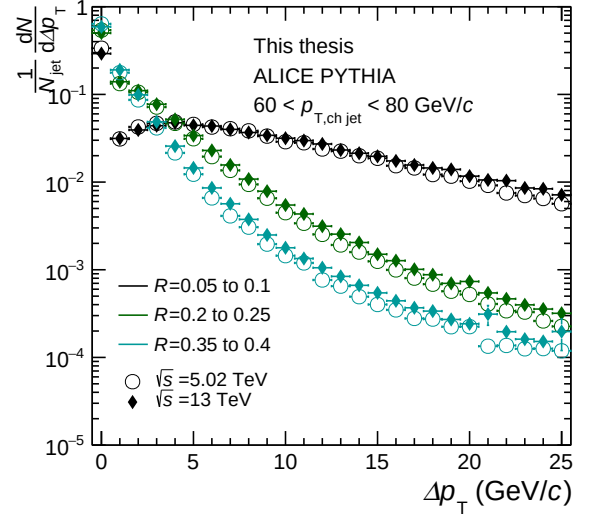
In heavy-ion collisions, jet energy flow measurements at large angles are challenging due to the presence of significant combinatorial background. Fluctuations of this background can lead to significant contamination of the measurement at low jet momenta especially for jets with a large radius. These fluctuations blur the correspondence between the true signal and reconstructed distribution as it can be seen in the response matrix projections (see Fig. 57 and 58) as well as the jet energy recovery distributions (see Fig. 59a). The difficulty in retrieving this correspondence manifested in insufficient convergence of the closure tests for the large jets (see Fig. 60 and 61). For that reason, the Pb-Pb measurement is restricted compared to the vacuum measurement in the jet momentum range of $60 \leq p_T < 80$ GeV/c and $R_{\text{jet}} \leq 0.25$.

As it was mentioned in Sec. 13.1, the presented jet energy flow measurements with the ALICE data were conducted in different energies for the two collision systems. To investigate the influence of this effect, Fig. 78a shows the comparison of Δp_T measurement in ALICE pp data at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV prior to corrections for detector effects. Within the available statistical accuracy, the two distributions are identical in the examined range of jet radius. To overcome the boundaries of limited statistical accuracy in this investigation, the same comparison was performed on PYTHIA simulations (Fig. 78b) which have been proven to describe the ALICE pp measurement very well. Both of these investigations demonstrate that the dependence on the system collision energy is mild and this difference cannot account for the observed levels of suppression between vacuum and Pb-Pb in terms of Δp_T . Additional plots relevant to this discussion point can be found in Appendix C.2.

Another difference between the compared energy flow distributions is an additional jet selection applied to the heavy-ion measurement. Specifically a requirement on the minimum transverse



(a) ALICE pp raw data



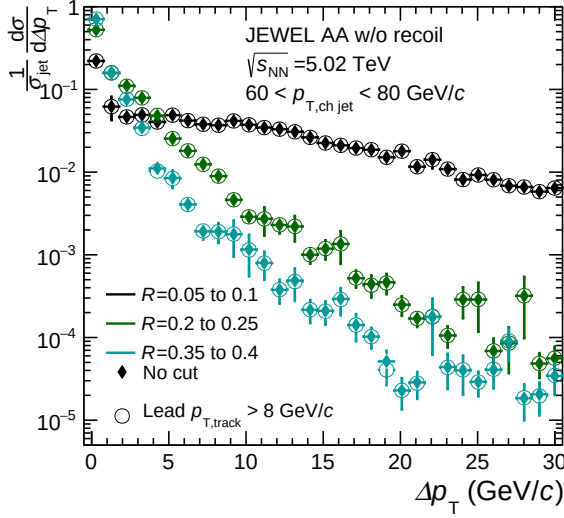
(b) PYTHIA simulations

Figure 78: Comparison of measured Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE pp data (left) and PYTHIA simulations (right) for different collision energies. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

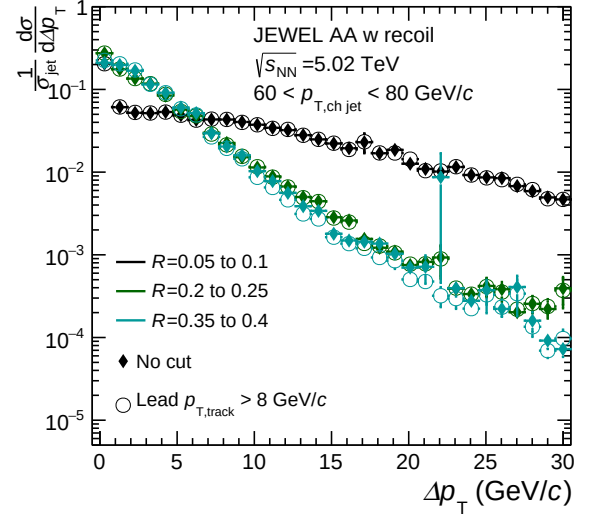
momentum of the leading hadron in the jet was introduced. This selection reduced the contamination of the measurement by the background fluctuations and it proved necessary to achieve satisfactory convergence of the closure tests for the Δp_T distributions in Pb-Pb collisions for small and intermediate sized jets. However, this requirement introduces a selection bias towards hard fragmentation. Since the pp measurement did not include such a requirement, the influence of this configuration difference has to be examined. It is worth noting that the associated evaluated systematic uncertainty was on the level of few percent and not the most significant for the Pb-Pb measurement (See Tab. 5). The influence of this difference was investigated with JEWEL AA simulations in terms of the Δp_T distributions (Fig. 79). For both recoil treatments, applying a cut on the momentum of the leading hadron in the jet has a very small or negligible effect on the Δp_T distributions. To sum up, both of the comparison caveats of different collision energies and lack of requirement on the jet's leading hadron momentum have a very small effect and do not change the earlier conclusions regarding the observation of a jet narrowing effect.

Concluding this chapter, there are some secondary observations about the presented measurements and the analysis procedure. The jet energy flow distributions for the smallest examined radial pair of $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ stand out from the rest of the distributions both in ALICE experimental data as well as in MC simulations. They are distinctly flatter than the ones from larger radial pairs and show a significant decrease between the first two distribution bins. These small radii probe the hard core of the shower which seems to be concentrated at $r < 0.1$. This thesis features the first application of the jet finding algorithms with such small radius, testing their limits regarding the Δp_T measurements.

A second feature of the results is that all of the presented distributions exhibit a distinct peak at the first bin of the distribution. The large bin width of 3 GeV/c raises the question whether the distribution is continuous or whether they reflect a special case of $\Delta p_T = 0$ GeV/c. Fig. 80 displays



(a) JEWEL AA w/o recoil



(b) JEWEL AA w recoil

Figure 79: Comparison of Δp_T distributions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ inclusive and exclusive of a $p_{T,\text{lead}}^{\text{track}} \geq 8$ GeV/c cut in JEWEL AA simulations. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

the Δp_T distribution in the peak region using finer binning. Due to a momentum cut of $p_T > 150$ MeV/c, jet pairs within the range $0 < \Delta p_T < 150$ MeV/c are shifted to $\Delta p_T = 0$. The distribution is normalized by bin width, except for the first bin, which is normalized by 150 MeV/c. While the distribution appears uniform for $\Delta p_T > 150$ MeV/c, the first bin remains an outlier. Although the momentum cut obscures the distribution's shape near zero, the uniformity across the remaining range suggests that jet pairs with no energy gain are a special and very probable scenario.

Thirdly, the ΔR distributions of the distance between the matched jets of different sizes in both of the ALICE measurements are very steeply decreasing. This demonstrates the remarkable success of the matching criterion based on the jet cone overlap in the $\eta - \phi$ plane.

Lastly, a few conclusions about some aspects of the analysis procedure are the following:

- The constituent method for background subtraction yielded considerably better results compared to the pedestal method. This was established through the resolution of the energy recovery distributions as well as the successful convergence of the closure tests. This conclusion is in agreement with earlier observations in other jet substructure studies.
- The approximation of a heavy-ion MC simulation through the embedding procedure of PYTHIA events in ALICE data required considerable computing power and runtime with the LEGO train system, posing technical restrictions on the Pb-Pb analysis.
- Since the presented analysis was conducted with ALICE Run 2 data, it benefited from the fact that the experimental data, MC simulations and analysis framework tools had already been calibrated, tested and benchmarked.

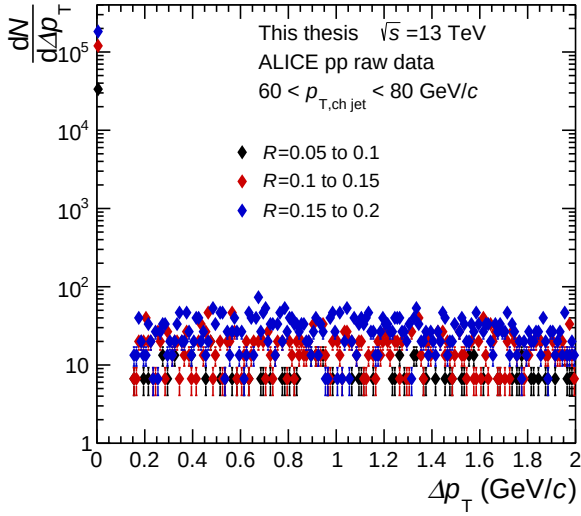
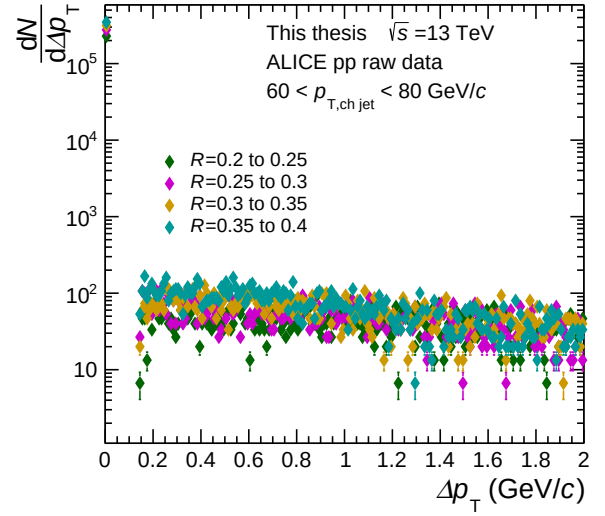
(a) $R_{\text{jet}} \leq 0.2$ (b) $0.2 \leq R_{\text{jet}} \leq 0.4$

Figure 80: Energy flow distributions of $\Delta p_T \leq 2$ GeV/c for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ ALICE pp data prior to corrections for detector effects. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

Part V

Summary & Outlook

14 Summary and the follow-up options

This chapter includes a summary of the research motivation, the developed analysis and its results in Sec. 14.1. Sec. 14.2 is dedicated to a few options that would serve as follow up investigations or extensions of the research presented in this dissertation.

14.1 Summing up

The research presented in this dissertation is dedicated to the study of the strong nuclear force in extreme conditions of temperature and density. Specifically, this work describes the analysis of ALICE experimental data and MC simulations to study the phenomenon of jet quenching in heavy-ion collisions. Jet quenching refers to the phenomenon of jet modification in heavy-ion collisions compared to the vacuum case of pp collisions. This modification originates from the interaction of the jets with the medium of deconfined matter that is produced in heavy-ion collisions. Two manifestations of jet quenching are jet energy loss and alteration of the jet substructure.

In this dissertation, a new jet observable was defined and measured with ALICE pp and Pb-Pb data to study jet quenching and its dependence on the jet radius. The observable of jet energy flow is defined as the difference in transverse momentum between a small (R) and a large jet ($R' > R$),

$$\Delta p_T = p_{T,R'} - p_{T,R}, \quad (23)$$

which probe the same parton shower. In order to ensure that the same shower is probed by the two jets, there is a requirement of sufficient jet cone overlap in the $\eta - \phi$ plane. By performing this measurement for a sequence of jet radii which differ by a small distance ($R_{\text{step}} = 0.05$) and ensuring that the jet axes of the analysed pair are almost aligned, the observable tracks the flow of energy as the reconstructed jet cone expands around a parton shower. In heavy-ion collisions there are at least two competing mechanisms that modify the parton shower angular structure. On the one hand, a parton shower with a wide opening angle would be resolved by the medium as multiple incoherent radiation sources and therefore experience higher levels of jet energy loss (wider jet suppression). On the other hand, medium induced radiation from a parton shower is expected to be distributed to wide angles with respect to the jet axis (large angle recapture). An energy flow measurement in pp collisions serves as the reference to study the modification due to jet quenching in heavy-ion collisions. The first mechanism would lead to a suppression in jet energy flow compared to the vacuum case while redistribution of gluon radiation at large angles and recapture with large jet cones would lead to an energy flow enhancement.

The sensitivity of this measurement to the medium effects was investigated in studies with the JEWEL jet quenching model. JEWEL is a Monte Carlo event generator which simulates the QCD jet evolution in heavy-ion collisions. Particularly, the model incorporates the medium response through the recoil of medium particles in their scatterings with the jet constituents. Jet energy flow measurements in JEWEL showed that the observable is sensitive to jet quenching but also provides distinct predictions for the recoil inclusive and exclusive cases.

The Δp_T measurements with the ALICE pp data showed that the mean energy flow is monotonically decreasing with an increase of the jet radius. The measurement confirmed previous observations that the majority of the jet energy is concentrated in a *hard core* around the jet axis ($r \leq 0.1$). This energy flow vacuum measurement is very well described by both the PYTHIA8 and HERWIG models despite their differences in parton shower ordering and hadronisation mechanisms. This agreement could signify either the insensitivity of the observable to the implementation of these mechanisms or the masking of their effect by the tuning of the models.

The corresponding jet energy flow measurement with the ALICE Pb-Pb data in small jet radii show a similar energy concentration near the jet axis. In heavy-ion collisions, the mean energy flow decreases more steeply with increasing jet radius, indicating a narrower jet energy profile than in pp collisions. Within the examined range of jet radii, no broadening effect was found. Comparing to predictions from the JEWEL MC generator, for both recoil modes the model shows a steeply decreasing Δp_T distribution which however underestimates the number of jets with no energy gain ($\Delta p_T = 0$), compensating with a flatter tail. The same observation holds for the JEWEL vacuum simulations compared to the experimental pp measurement. Despite the discrepancies in the measurements of pp and Pb-Pb collisions, the relative energy flow modification between vacuum and heavy-ion collisions is well captured by the model, particularly in the recoil-exclusive mode.

The surprising success of the recoil-exclusive mode, which neglects the medium response, has also been observed in other observables like the R_{AA} double ratio. On the other hand, it has been shown that jet shape measurements are better described by models that include medium response. In those cases the recoil-inclusive mode provides better agreement. Further work on the JEWEL model is required to clarify whether these differences stem from shortcomings in the current implementation of the physics mechanisms or whether they can be addressed by model tuning to describe recent experimental results. It would also be worthwhile to extend energy flow measurements in Pb-Pb collisions to larger jet radii to explore the redistribution of medium-induced radiation at larger angles. This requires an improved treatment or further suppression of background fluctuations in the measurement.

The jet energy flow observable introduced in this dissertation explores the energy distribution within the jet cone. The observable definition and the examined phase space in R_{jet} complements previous measurements of the R_{AA} nuclear modification double ratio, the jet density profile $\rho(r)$ and the subjet momentum fraction z_r . The reported results confirm the narrowing of the jet profile in heavy-ion collisions, discovered in earlier CMS $\rho(r)$ measurements. The important contribution of the Δp_T measurement is its sensitivity to event-by-event fluctuations of energy flow within the jets. This aspect is not accessible with the previous jet shape studies which are not measured on a jet-by-jet basis. In conclusion the presented results demonstrate the potential of the jet energy flow observable for future jet quenching investigations either as a standalone study or in conjunction with other jet substructure observables.

14.2 Outlook and future plans

The modification of the jet energy flow is studied through the comparison of the respective Δp_T distributions in pp and Pb-Pb collisions. The comparison of Δp_T distributions for small jet radii ($R_{\text{jet}} < 0.25$) presented in this work, showed a narrowing of the intra-jet energy flow distribution in heavy-ion collisions. It would be very interesting to extend these measurements to larger jet radii in future work in order to investigate a possible re-distribution of the radiation at large angles. Extensions of the energy flow measurement in both collision systems towards lower and higher jet momenta would allow the study of the p_T dependence. Additionally the measurement of jet energy flow of more energetic and larger jets would enable a further comparison with the earlier jet shape measurements. More importantly it would extend the conclusions of those studies by measuring the fluctuations of the energy flow on a jet by jet basis in addition to the mean energy flow. Furthermore, the interpretation of the energy flow measurement in Pb-Pb would greatly benefit from comparisons with models that implement different energy loss mechanisms and medium response treatments, to further constrain the specific mechanisms contributing to jet

quenching.

A new measurement of the jet energy flow for larger jets in a heavy-ion environment would require an efficient method to treat the background contamination. The background fluctuations impeded the present measurement as it was shown with the non-convergence of the closure tests and the poor correspondence of the response for large jets (see Sec. 11.4). Although a refinement of the analysis procedures described in this work could be pursued, an application of newer background subtraction methods would be interesting. For example, a machine-learning method to remove the background contamination in the measurement of the nuclear modification factor has already shown promising results [197, 213]. Another option is the modification of the jet matching procedure to include a requirement on a shared p_T fraction of the jet candidates along with the geometrical overlap requirement. This criterion would exclude any background combinatorial jets and improve the response matrix correspondence between generator and reconstructed level. Additionally, it would be interesting to study the effect of a shared p_T fraction requirement on the ΔR distributions for the matched jets of different radii.

The options outlined above can be viewed as direct extensions of the research presented in this dissertation. There are also options of expanding the jet energy flow fluctuation studies in different configurations or collision systems. Specifically, it would be interesting to study the modification of the Δp_T distributions as a function of the event multiplicity or the collision system size. For example, measurements of the jet energy flow could be made as function of centrality in heavy-ion collisions. Also, the reported results could be compared with the Δp_T measurements in p-Pb collisions or pp collisions with multiplicity. Modification observations in those systems would point to evidence of jet quenching in small systems, a experimental signature that has proven elusive so far. Furthermore, an intriguing option would be performing the jet energy flow measurement in gamma-jet events. Since photons do not carry color charge, they do not interact with the QGP and therefore serve as a direct probe of the jet's initiating parton prior to its interaction with the medium. Additionally, the jets studied in these configurations would be quark-initiated jets. Their comparison with the inclusive Δp_T would help characterize the effect of the initiating parton on the shower's angular structure.

The presented measurements of the energy flow distribution of the smallest jet radii showed there is a narrow hard core around the jet axis. A new energy flow measurement focused on small radii with smaller radial steps ($\delta R < 0.05$) could help find the edge of this jet core. Also this measurement would explore the abrupt slope transition observed between the Δp_T distributions of $R_{\text{small}} = 0.05$ and $R_{\text{small}} = 0.1$.

Lastly, the jet energy flow fluctuations is a new experimental tool to study the jet quenching in heavy-ion collisions, which can be used in conjunction with other jet substructure observables. A promising candidate would be the study of the correlation with the subjet momentum fraction since the two observables share multiple definition elements and both explore the energy distribution within the jet.

Summary in English

The research presented in this dissertation contributes to the study of the strong nuclear force in extreme conditions similar to those in the early stages of the universe. Specifically it concerns the analysis of model simulations and experimental data measured with the ALICE (A Large Ion Collider Experiment) detector at the Large Hadron Collider (LHC) experiment at CERN. Experiments where fundamental particles collide at very high energies are excellent testing grounds of the strong force interaction. Quantum Chromo-Dynamics (QCD) is the quantum field theory that describes that force and follows the SU(3) gauge symmetry. The associated charge of the strong force is called "color" and its carriers, quarks, anti-quarks and gluons are referred to as partons. At long distances the strong force is so large that leads to the partons becoming confined in color-neutral hadron configurations. These hadrons are the particles observed in nature and measured by the experimental detectors.

In high energy collisions, the scattering takes place between the partons of the colliding nucleons. Scatterings where the exchanged momentum is significantly larger than the scale of the strong interaction, Λ_{QCD} , are referred to as hard scatterings. In hard scatterings the interacting partons will move in opposite directions and produce particle showers through QCD radiation processes. As these parton showers evolve, the energy is divided over more partons and eventually the shower constituents are confined in hadronic configurations (hadronisation). Since the detectors in particle experiments measure only hadrons, information of the interactions at the parton level are not directly accessible. Jet finding algorithms can be used to cluster together the hadrons originating from a single parton shower and therefore probe the initially inaccessible parton level information. These jet algorithms applied on the collimated hadron sprays cluster particles inside cones of a fixed radius in the rapidity-azimuth plane.

When the collision takes place between heavy ions there is a very large number of colliding nucleons creating conditions of extreme temperature and nuclear matter density. Under this conditions a medium of deconfined quarks and gluons is created. This state of matter is called Quark-Gluon-Plasma and behaves as a perfect liquid. In a heavy-ion collision, the hard-scattering partons will interact with the medium constituents since they also carry color-charge. These medium interactions through elastic scatterings or medium-induced radiation result in the modification of the parton shower structure and energy loss for the shower's initiating hard parton. As a result, jets reconstructed in heavy-ion collisions will have a modified structure and experience energy loss compared to their counterparts in vacuum. The phenomena of jet energy loss and modification are referred to as jet quenching.

In this dissertation, a new jet observable was defined and measured with ALICE pp and Pb-Pb data to study jet quenching and its dependence on the jet radius. The observable of jet energy flow is defined as the difference in transverse momentum between a small (R) and a large jet ($R' > R$),

$$\Delta p_T = p_{T,R'} - p_{T,R} ,$$

which probe the same parton shower. In order to ensure that the same shower is probed by the two jets, there is a requirement of sufficient jet cone overlap in the $\eta - \phi$ plane. By performing this measurement for a sequence of jet radii which differ by a small distance ($R_{\text{step}} = 0.05$) and ensuring that the jet axes of the analysed pair are almost aligned, the observable tracks the flow of energy as the reconstructed jet cone expands around a parton shower. In heavy-ion collisions there are at least two competing mechanisms that modify the parton shower angular structure. On the one hand, a parton shower with a wide opening angle would be resolved by the medium as multiple incoherent radiation sources and therefore experience higher levels of jet energy loss

(wider jet suppression). On the other hand, medium induced radiation from a parton shower is expected to be distributed to wide angles with respect to the jet axis (large angle recapture). An energy flow measurement in pp collisions serves as the reference to study the modification due to jet quenching in heavy-ion collisions. The first mechanism would lead to a suppression in jet energy flow compared to the vacuum case while redistribution of gluon radiation at large angles and recapture with large jet cones would lead to an energy flow enhancement.

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The surprising success of the recoil-exclusive mode, which neglects the medium response, has also been observed in other observables like the R_{AA} double ratio. On the other hand, it has been shown that jet shape measurements are better described by models that include medium response. In those cases the recoil-inclusive mode provides better agreement. Further work on the JEWEL model is required to clarify whether these differences stem from shortcomings in the current implementation of the physics mechanisms or whether they can be addressed by model tuning to describe recent experimental results. It would also be worthwhile to extend energy flow measurements in Pb-Pb collisions to larger jet radii to explore the redistribution of medium-induced radiation at larger angles. This requires an improved treatment or further suppression of background fluctuations in the measurement.

The jet energy flow observable introduced in this dissertation explores the energy distribution within the jet cone. The observable definition and the examined phase space in R_{jet} complements previous measurements of the R_{AA} nuclear modification double ratio, the jet density profile $\rho(r)$ and the subjet momentum fraction z_r . The reported results confirm the narrowing of the jet profile in heavy-ion collisions, discovered in earlier CMS $\rho(r)$ measurements. The important contribution of the Δp_T measurement is its sensitivity to event-by-event fluctuations of energy flow within the jets. This aspect is not accessible with the previous jet shape studies which are measured on a

jet-by-jet basis. In conclusion the presented results demonstrate the potential of the jet energy flow observable for future jet quenching investigations either as a standalone study or in conjunction with other jet substructure observables.

Samenvatting in het nederlands

Het onderzoek gepresenteerd in dit proefschrift draagt bij aan de studie van de sterke kernkracht onder extreme omstandigheden die vergelijkbaar zijn met die in de vroege stadia van het universum. Specifiek betreft het de analyse van modelsimulaties en experimentele data gemeten met de ALICE (A Large Ion Collider Experiment) detector bij het Large Hadron Collider (LHC) experiment bij CERN. Experimenten waarbij fundamentele deeltjes botsen bij zeer hoge energieën zijn uitstekende testgronden voor de interactie van de sterke kracht. Kwantumchromodynamica (QCD) is de kwantumveldentheorie die deze kracht beschrijft en volgt de SU(3) iksymmetrie. De bijbehorende lading van de sterke kracht wordt "kleur" genoemd en de dragers ervan, quarks, anti-quarks en gluonen, worden aangeduid als partonen. Op lange afstanden is de sterke kracht zo groot dat de partonen opgesloten raken in kleur-neutrale hadronconfiguraties. Deze hadronen zijn de deeltjes die in de natuur worden waargenomen en gemeten door experimentele detectoren.

In hoogenenergetische botsingen vindt de verstrooiing plaats tussen de partonen van de botsende nucleonen. Verstrooiingen waarbij het uitgewisselde momentum aanzienlijk groter is dan de schaal van de sterke interactie, Λ_{QCD} , worden harde verstrooiingen genoemd. Bij harde verstrooiingen bewegen de interagerende partonen in tegengestelde richtingen en produceren ze deeltjesstromen door QCD-stralingsprocessen. Terwijl deze partonenstromen zich ontwikkelen, wordt de energie verdeeld over meer partonen en uiteindelijk worden de stromende bestanddelen opgesloten in hadronische configuraties (hadronisatie). Omdat de detectoren in deeltjesexperimenten alleen hadronen meten, is informatie over de interacties op partonniveau niet direct toegankelijk. Jet-vindingsalgoritmen kunnen worden gebruikt om de hadronen die afkomstig zijn van één partonenstroom te clusteren en zo de aanvankelijk ontoegankelijke informatie op partonniveau te onderzoeken. Deze jet-algoritmen, toegepast op de geconcentreerde hadronenstralen, clusteren deeltjes binnen kegels met een vaste straal in het rapiditeit-azimuth vlak.

Wanneer de botsing plaatsvindt tussen zware ionen, is er een zeer groot aantal botsende nucleonen, waardoor omstandigheden van extreme temperatuur en nucleaire materiedichtheid ontstaan. Onder deze omstandigheden wordt een medium van vrijgekomen quarks en gluonen gecreëerd. Deze toestandsmaterie wordt Quark-Gluon Plasma genoemd en gedraagt zich als een perfecte vloeistof. Bij een zware-ion botsing zullen de hard verstrooide partonen interageren met de bestanddelen van het medium, aangezien ze ook kleurlading dragen. Deze mediuminteracties door elastische verstrooiingen of door het medium geïnduceerde straling resulteren in de aanpassing van de partonenstroomstructuur en energieverlies voor het hard verstrooide parton dat de stroom initieert. Als gevolg hiervan zullen jets gereconstrueerd in zware-ionbotsingen een aangepaste structuur hebben en energieverlies ervaren vergeleken met hun tegenhangers in vacuüm. Het fenomeen van jet-energieverlies en aanpassing wordt aangeduid als jet quenching.

In dit proefschrift werd een nieuwe jet-observeerbare gedefinieerd en gemeten met ALICE pp- en Pb-Pb-gegevens om jet quenching en de afhankelijkheid ervan van de jet-straal te bestuderen. De observeerbare jet-energie-stroom wordt gedefinieerd als het verschil in transversale impuls tussen een kleine (R) en een grote jet ($R' > R$),

$$\Delta p_T = p_{T,R'} - p_{T,R} ,$$

die dezelfde partonenstroom onderzoekt. Om ervoor te zorgen dat dezelfde stroom door de twee jets wordt onderzocht, is er een eis van voldoende jet-kegeloverlap in het $\eta - \phi$ vlak. Door deze meting uit te voeren voor een reeks jet-stralen die met een kleine afstand ($R_{\text{step}} = 0.05$) van elkaar verschillen en ervoor te zorgen dat de jet-assen van het geanalyseerde paar bijna uitgelijnd zijn, volgt de observeerbare de energiestroom naarmate de gereconstrueerde jet-kegel zich uitbreidt rond

een partonenstroom. Bij zware-ionbotsingen zijn er minstens twee concurrerende mechanismen die de hoekstructuur van de partonenstroom aanpassen. Enerzijds zou een partonenstroom met een wijde openingshoek door het medium worden waargenomen als meerdere onsamenhangende stralingsbronnen en daarom hogere niveaus van jet-energieverlies ervaren (wijder jet-onderdrukking). Anderzijds wordt verwacht dat door het medium geïnduceerde straling van een partonenstroom wordt verspreid naar brede hoeken ten opzichte van de jet-as (grothoek-heropname). Een energiestroommeting in pp-botsingen dient als referentie om de aanpassing als gevolg van jet quenching bij zware-ionbotsingen te bestuderen. Het eerste mechanisme zou leiden tot een onderdrukking in de jet-energiestroom vergeleken met het vacuümgeval, terwijl herverdeling van gluonstraling onder grote hoeken en heropname met grote jet-kegels zou leiden tot een toename van de energiestroom.

De gevoeligheid van deze meting voor de effecten van het medium werd onderzocht in studies met het JEWEL jet quenching-model. JEWEL is een Monte Carlo-gebeurtenisgenerator die de evolutie van QCD-jets in zware-ionbotsingen simuleert. Het model integreert met name de mediumrespons door de terugslag van mediumdeeltjes in hun verstrooiingen met de jet-bestanddelen. Jet-energiestroommetingen in JEWEL toonden aan dat de observeerbare gevoelig is voor jet quenching, maar ook onderscheidende voorspellingen biedt voor de terugslag-inclusieve en exclusieve gevallen.

De Δp_T -metingen met de ALICE pp-gegevens toonden aan dat de gemiddelde energiestroom monotoon afneemt met een toename van de jet-straal. De meting bevestigde eerdere observaties dat het merendeel van de jet-energie geconcentreerd is in een "harde kern" rond de jet-as ($r \leq 0.1$). Deze vacuümmeting van de energiestroom wordt zeer goed beschreven door zowel de PYTHIA8- als HERWIG-modellen, ondanks hun verschillen in partonenstroomordening en hadronisatiemechanismen. Deze overeenstemming zou kunnen betekenen dat de observeerbare ongevoelig is voor de implementatie van deze mechanismen of dat hun effect wordt gemaskeerd door het afstemmen van de modellen.

De overeenkomstige meting van de jet-energiedoorstroming met de ALICE Pb-Pb-data voor kleine jetstralen toont een vergelijkbare energieconcentratie nabij de jet-as. In zware-ionbotsingen daalt de gemiddelde energiedoorstroming steiler met toenemende jetstraal, wat wijst op een smaller energieprofiel dan in pp-botsingen. Binnen het onderzochte bereik van jetstralen werd geen verbredingseffect gevonden. Vergeleken met de voorspellingen van de JEWEL MC-generator, toont het model voor beide terugstootmodi een steil aflopende Δp_T -verdeling die echter het aantal jets zonder energieverhoging ($\Delta p_T = 0$) onderschat, gecompenseerd door een vlakkere staart. Dezelfde observatie geldt voor de JEWEL-vacuümsimulaties in vergelijking met de experimentele pp-metingen. Ondanks de discrepanties in de metingen van pp- en Pb-Pb-botsingen, wordt de relatieve energiedoorstromingsmodificatie tussen vacuüm- en zware-ionbotsingen goed vastgelegd door het model, met name in de exclusieve terugstootmodus.

Het verrassende succes van de exclusieve terugstootmodus, die geen rekening houdt met de mediumrespons, is ook waargenomen bij andere observabelen zoals de R_{AA} -dubbele ratio. Aan de andere kant is aangetoond dat metingen van jetvormen beter worden beschreven door modellen die de mediumrespons meenemen. In die gevallen biedt de inclusieve terugstootmodus een betere overeenstemming. Verdere ontwikkeling van het JEWEL-model is vereist om te verduidelijken of deze verschillen voortkomen uit tekortkomingen in de huidige implementatie van de fysische mechanismen of dat ze kunnen worden aangepakt door modelafstemming om recente experimentele resultaten te beschrijven. Het zou ook de moeite waard zijn om metingen van de energiedoorstroming in Pb-Pb-botsingen uit te breiden naar grotere jetstralen om de redistributie van mediumgeïnduceerde straling op grotere hoeken te verkennen. Dit vereist een verbeterde behandeling of verdere onderdrukking van achtergrondfluctuaties in de meting.

De jet-energiedoorstromingsobservabele die in dit proefschrift wordt geïntroduceerd, verkent de

energiedistributie binnen de jetkegel. De definitie van de observabele en de onderzochte faseruimte in R_{jet} vormt een aanvulling op eerdere metingen van de nucleaire modificatiedubbele ratio R_{AA} , het jetdichtheidsprofiel $\rho(r)$ en de substraalmomentumfractie z_r . De gerapporteerde resultaten bevestigen de vernauwing van het jetprofiel in zware-ionbotsingen, zoals ontdekt in eerdere CMS $\rho(r)$ -metingen. De belangrijke bijdrage van de Δp_T -meting is de gevoeligheid ervan voor gebeurtenis-tot-gebeurtenis fluctuaties van de energiedoorstroming binnen de jets. Dit aspect is niet toegankelijk met de eerdere studies van jetvormen die per jet worden gemeten. Samenvattend tonen de gepresenteerde resultaten het potentieel aan van de jet-energiedoorstromingsobservabele voor toekomstige onderzoeken naar jet-quenching, hetzij als een op zichzelf staande studie, hetzij in combinatie met andere jet-substructuur-observabelen.

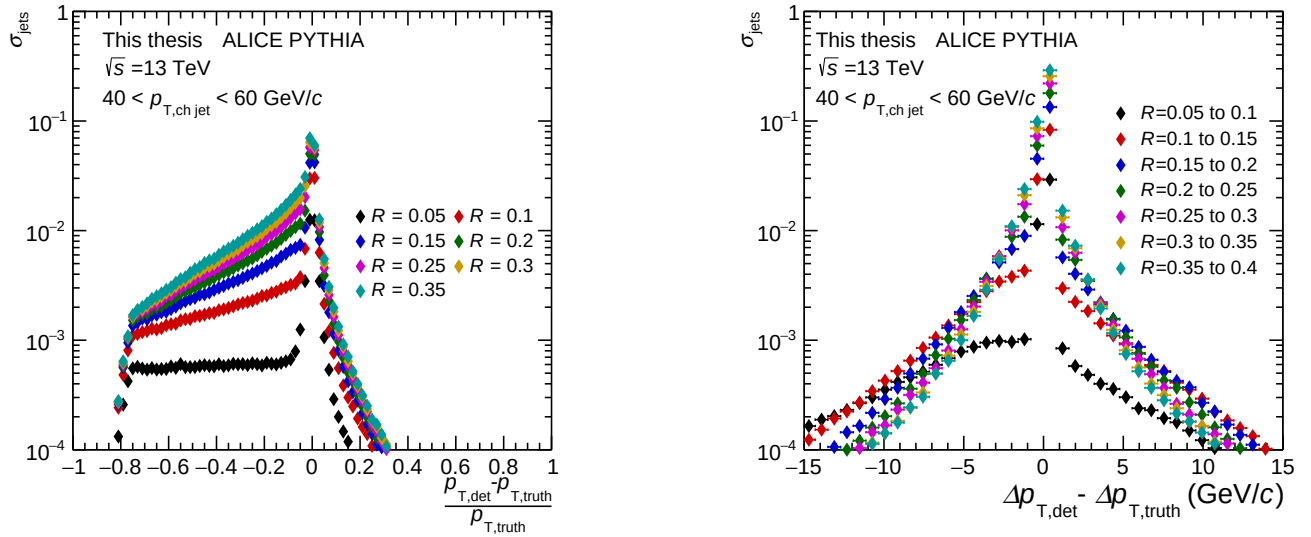
Appendix

A - Supplemental plots for the pp measurement

This appendix chapter features additional plots related to the energy flow measurement with ALICE pp data. Particularly, supplemental plots of the analysis corrections and the convergence of closure tests are presented in Sec. A.1 and A.2, respectively. An overview of the systematic uncertainties not shown in the main text can be found in Sec. A.3. Lastly, Sec. A.4 completes the picture of the model comparisons for the reference measurement.

A.1 - Correction plots for ALICE pp data

The jet energy recovery distributions for p_T and Δp_T with a selection on the jet momentum $40 \leq p_T < 60$ GeV/c are shown in Fig. 81. The distributions are qualitatively similar to the ones shown in Fig. 47 of the main text.



(a) Jet energy recovery distributions

(b) Jet energy flow resolution

Figure 81: Jet energy resolution (left) and Δp_T resolution (right) plots for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE PYTHIA simulations. For both plots a selection on the jet p_T of the narrow jet, $40 \leq p_T < 60$ GeV/c, is applied.

The response matrix projections in terms for jet p_T for the jet radii which were not included in Fig. 45 of the main text are shown in Fig. 82.

The corresponding projections with respect to Δp_T for the same jet radial pairs are presented in Fig. 83. Fig. 84 and 85 correspond to the response matrix projections in terms of Δp_T for jets with momentum $40 \leq p_T < 60$ GeV/c.

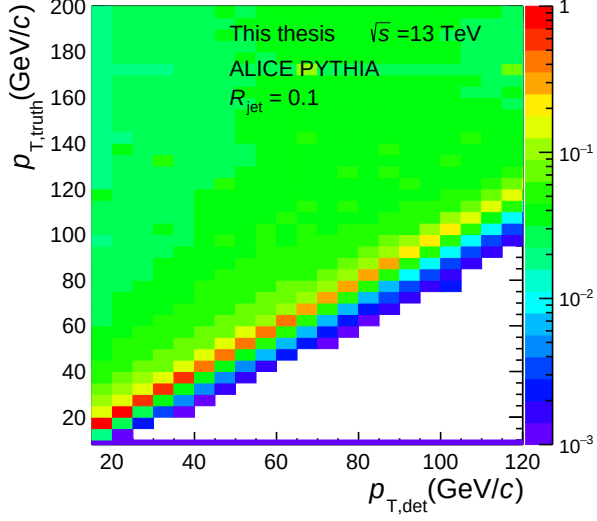
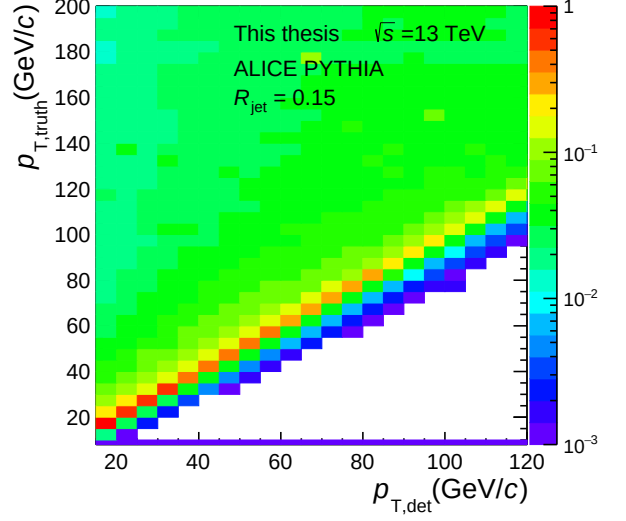
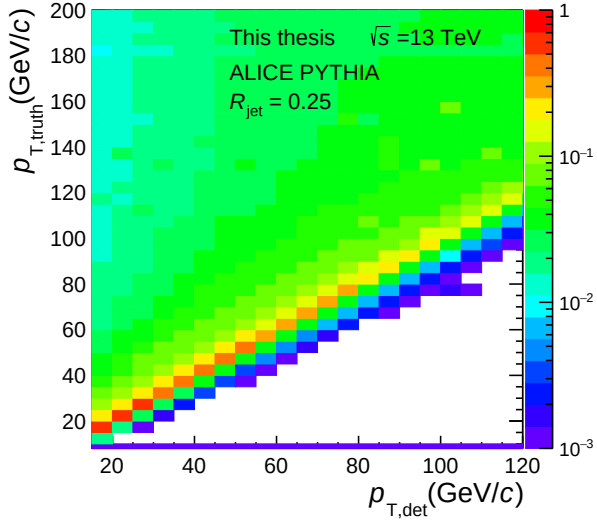
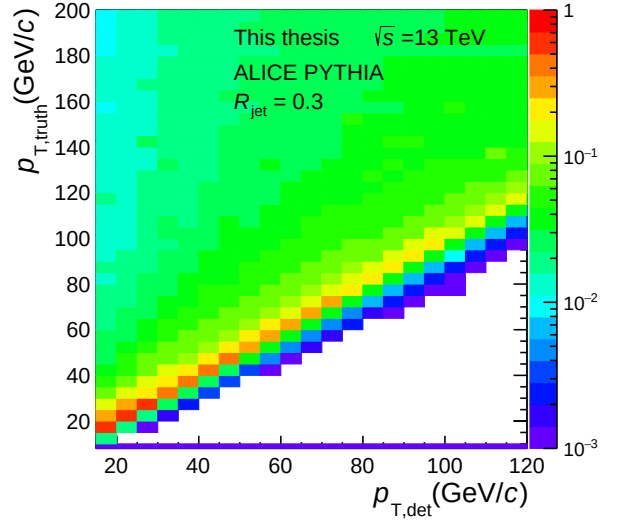
(a) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ (b) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.2$ (c) $R_{\text{jet}} = 0.25$ to $R_{\text{jet}} = 0.3$ (d) $R_{\text{jet}} = 0.3$ to $R_{\text{jet}} = 0.35$

Figure 82: Projections of the response matrix for p_T between truth and detector level in ALICE PYTHIA simulations for matched jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$.

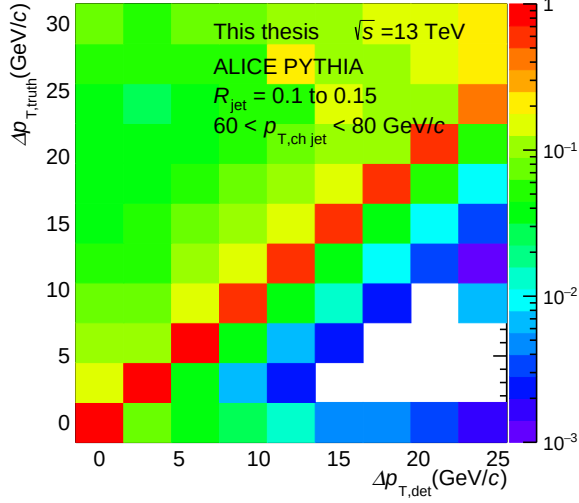
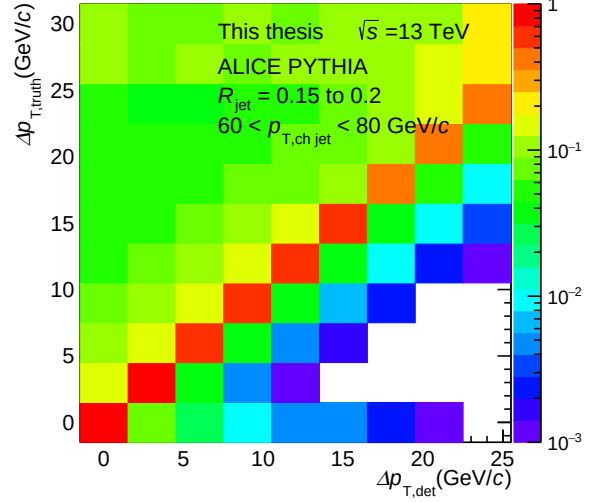
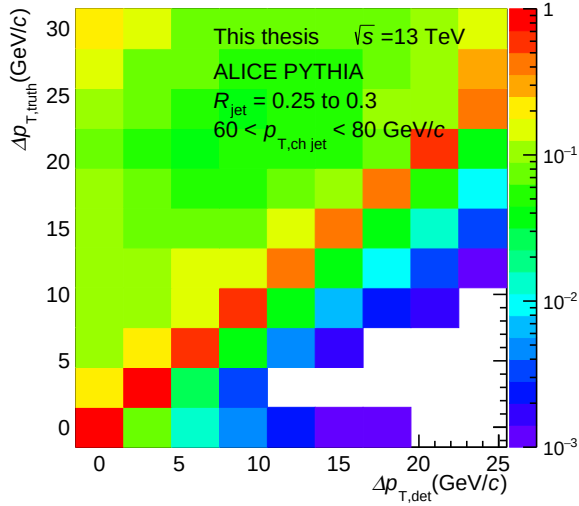
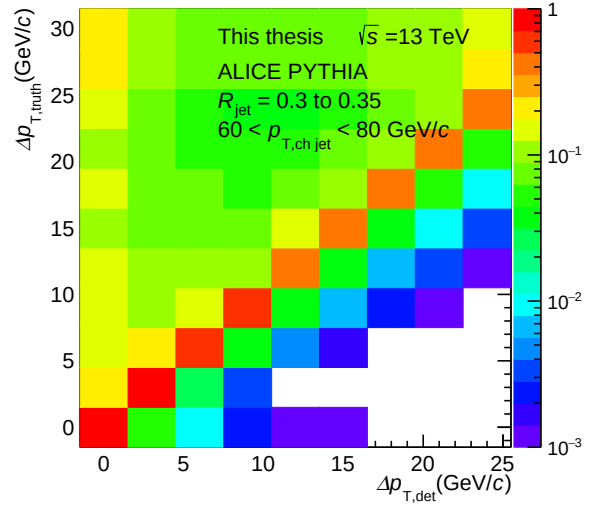
(a) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ (b) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.2$ (c) $R_{\text{jet}} = 0.25$ to $R_{\text{jet}} = 0.3$ (d) $R_{\text{jet}} = 0.3$ to $R_{\text{jet}} = 0.35$

Figure 83: Projections of the response matrix for Δp_T between truth and detector level in ALICE PYTHIA simulations for matched jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$. In all three panels a selection on the narrow jet's p_T at truth level, $60 \leq p_T < 80$ GeV/c, is applied.

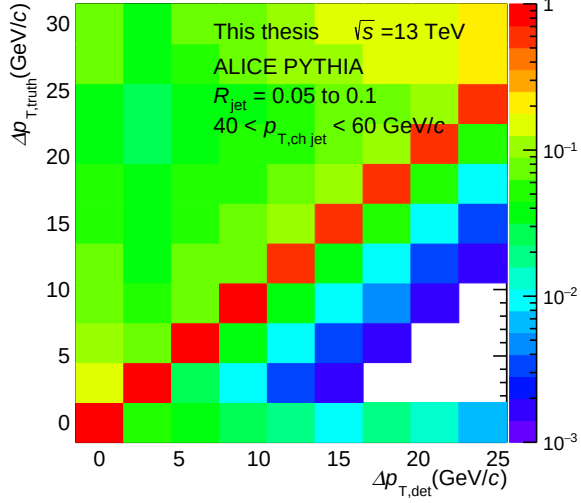
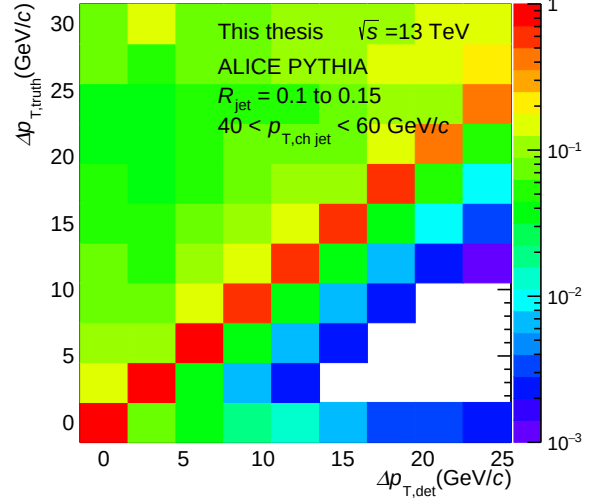
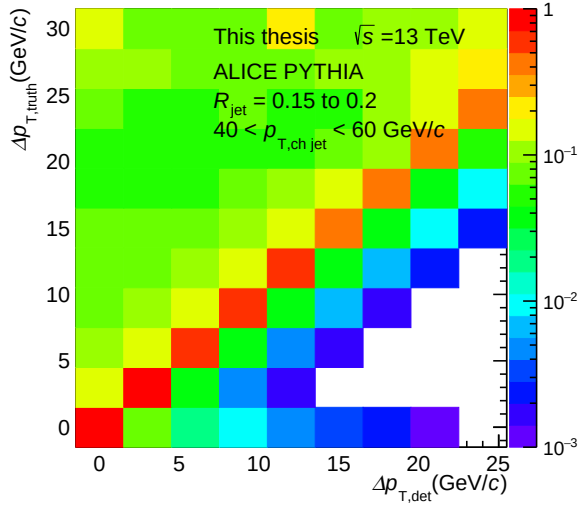
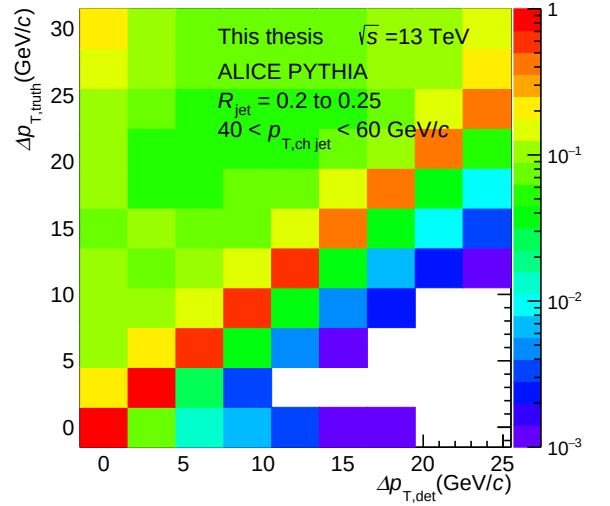
(a) $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$ (b) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ (c) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.2$ (d) $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$

Figure 84: Projections of the response matrix for Δp_T between truth and detector level in ALICE PYTHIA simulations for matched jet pairs with radius between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.25$. In all three panels a selection on the narrow jet's p_T at truth level, $40 \leq p_T < 60$ GeV/c, is applied.

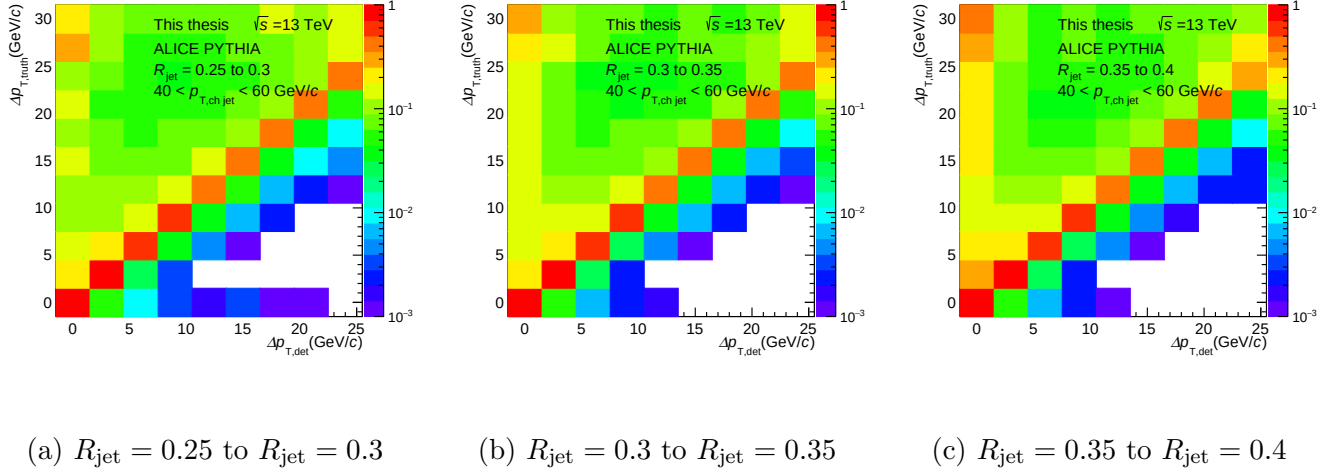


Figure 85: Projections of the response matrix for Δp_T between truth and detector level in ALICE PYTHIA simulations for matched jet pairs with radius between $R_{\text{jet}} = 0.25$ and $R_{\text{jet}} = 0.4$. In all three panels a selection on the narrow jet's p_T at truth level, $40 \leq p_T < 60$ GeV/c, is applied.

A.2 - Closure tests for ALICE PYTHIA

Convergence of closure tests is an important test to validate the unfolding procedure. The closure tests in both truth and reconstructed level for the ALICE PYTHIA simulations are shown in Fig. 86 and 88 respectively for jets with a momentum selection of $40 \leq p_T < 60$ GeV/c. In addition the closure tests for jets with $60 \leq p_T < 80$ GeV/c for the radial pairs which were not shown in Fig. 48 and 49 are featured in Fig. 87 and 87 of this section. All of these tests show sufficient convergence within the statistical uncertainties.

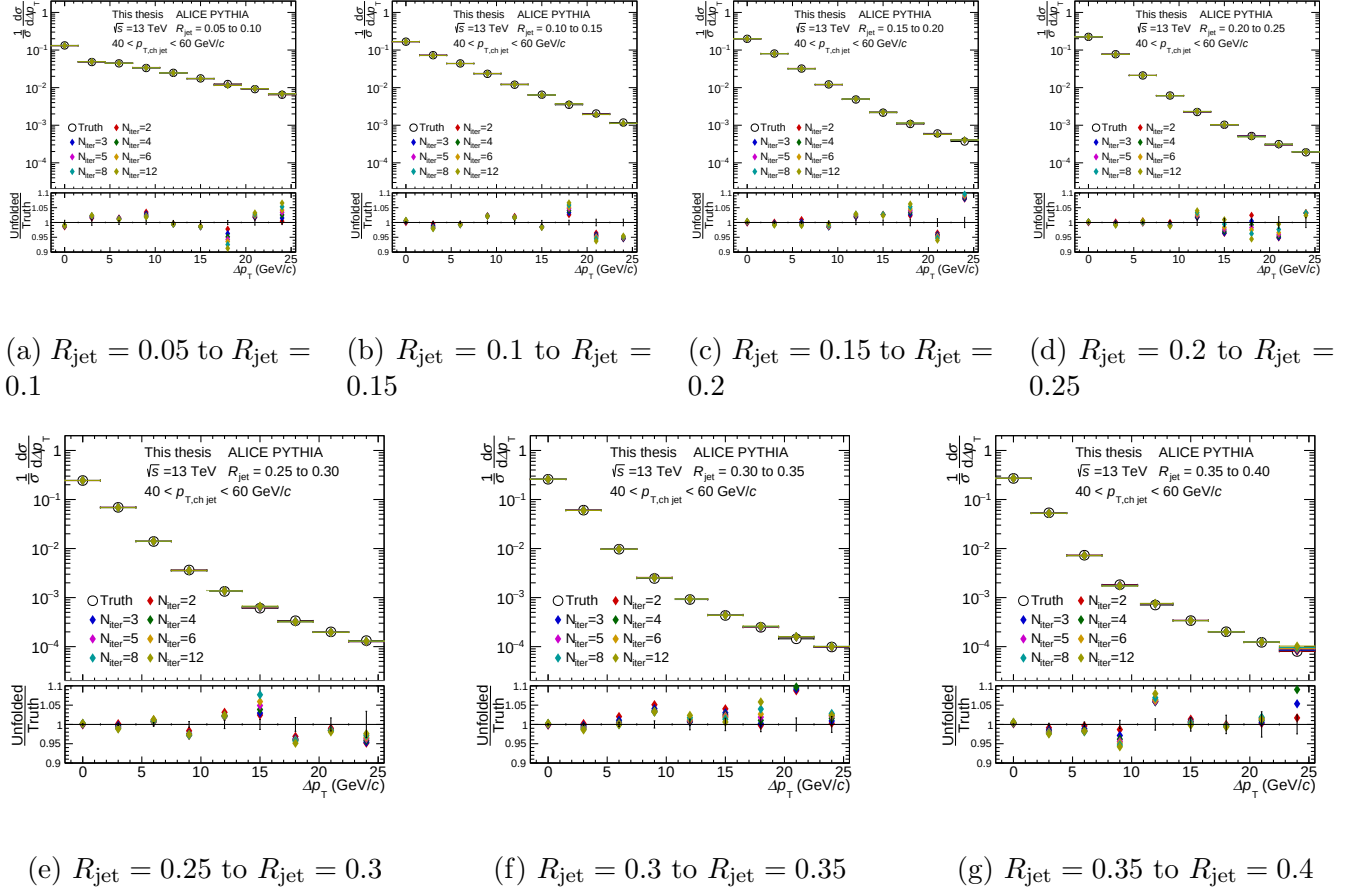


Figure 86: Performance of closure tests at the truth level for Δp_T distributions for jet pairs with radius between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE PYTHIA simulations. The bottom panels show the ratio between the unfolded and truth level distributions. In all seven panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

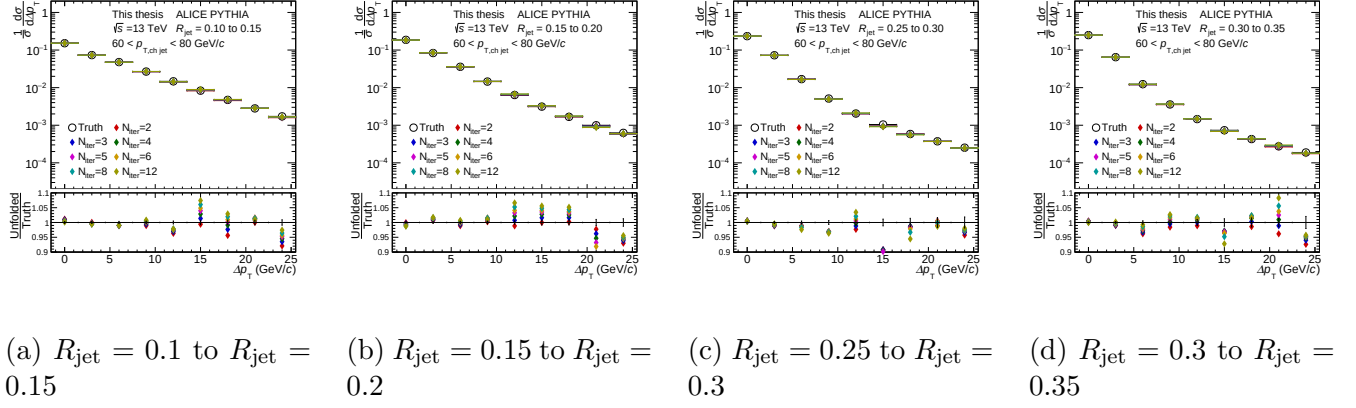


Figure 87: Performance of closure tests at the truth level for Δp_T distributions for jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$ in ALICE PYTHIA simulations. The bottom panels show the ratio between the unfolded and truth level distributions. In all four panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

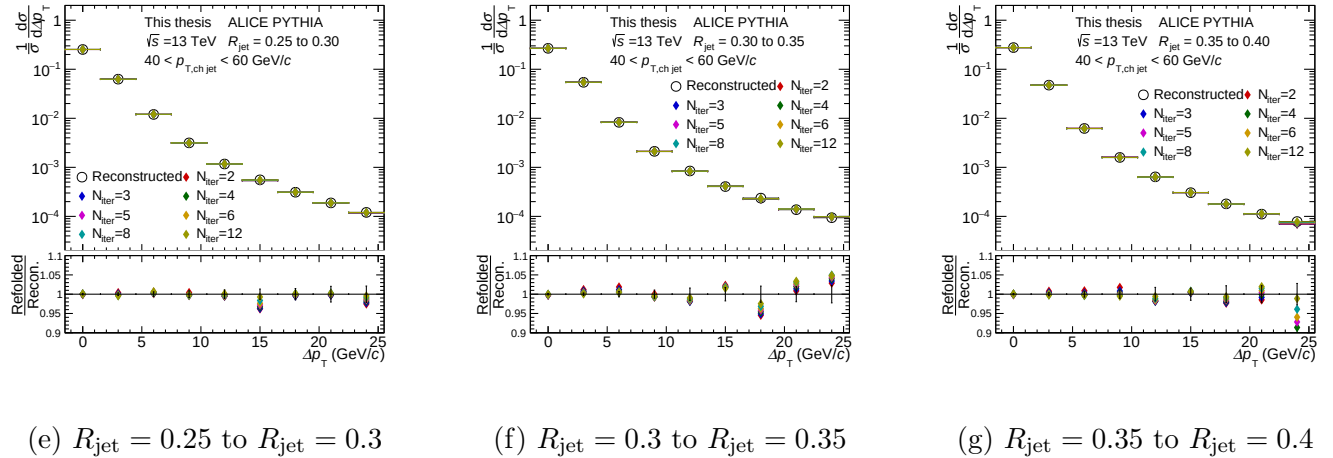
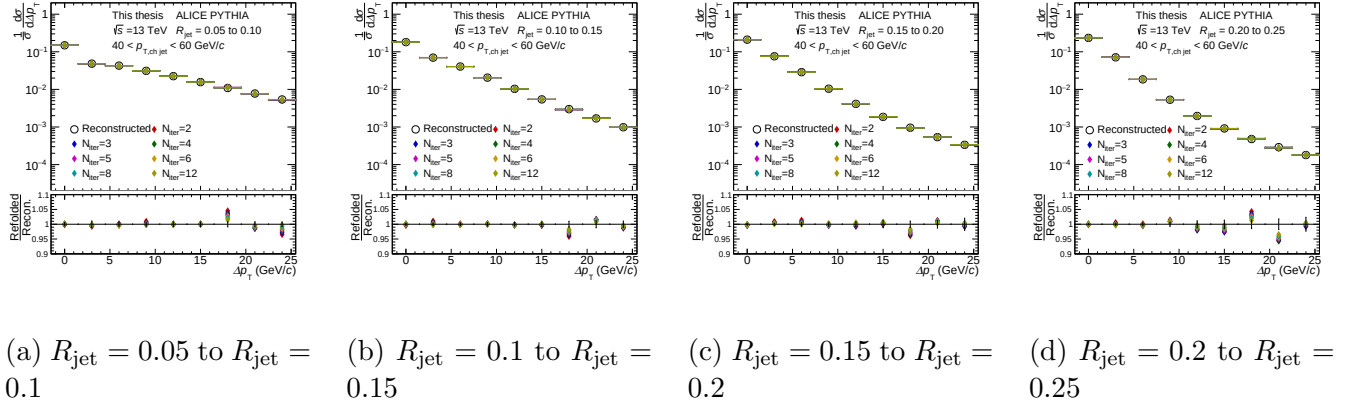


Figure 88: Performance of closure tests at the reconstructed level for Δp_T distributions for jet pairs with radius between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE PYTHIA simulations. The bottom panels show the ratio between the refolded and detector level distributions. In all seven panels, a jet p_T selection on the narrow jet, $40 \leq p_T < 60$ GeV/c, is applied.

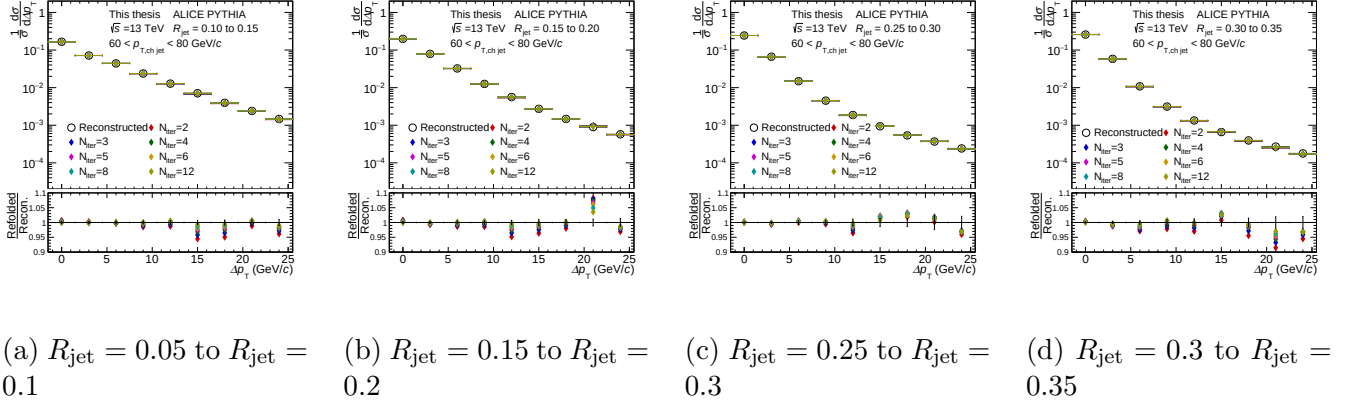


Figure 89: Performance of closure tests at the reconstructed level for Δp_T distributions for jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$ in ALICE PYTHIA simulations. The bottom panels show the ratio between the refolded and detector level distributions. In all four panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

A.3 - Systematic uncertainties for ALICE pp measurement

The calculated systematic uncertainties of the energy flow measurement with the ALICE pp data are outlined in Tab. 3 and 4. This section shows an overview of those contributions similar to Fig. 50 for the remaining jet radii in Fig. 90. Additionally, the overview of the systematic uncertainties and their dependence on Δp_T for all of the jet radial pairs for jets with a momentum selection of $40 \leq p_T < 60$ is presented in Fig. 91 of this section. In all of these plots the respective statistical uncertainty is plotted as well as a reference.

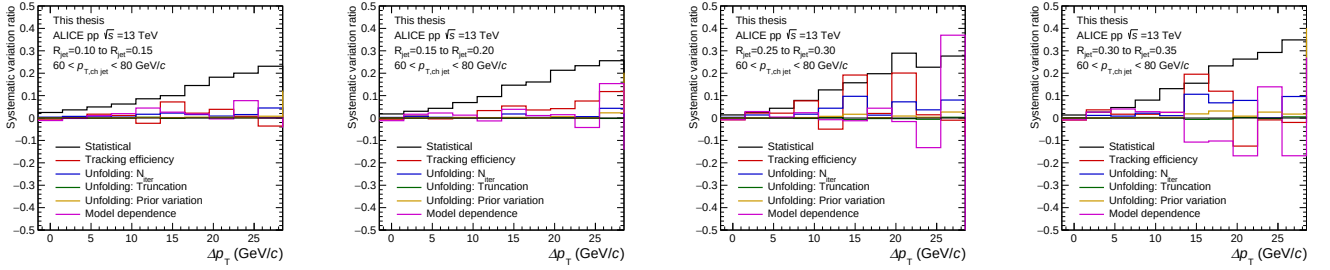


Figure 90: Overview of the relative systematic uncertainties for jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$. A selection to the jet p_T , $60 \leq p_T < 80$ GeV/c, of the narrow jet has been applied. The statistical uncertainty of the default unfolded distribution is also plotted as a reference.

A.4 - Model comparisons for ALICE pp measurement

The measured Δp_T distributions with ALICE pp data and their agreement with the PYTHIA8 and HERWIG model predictions for some radial cases and for the mean energy flow and its

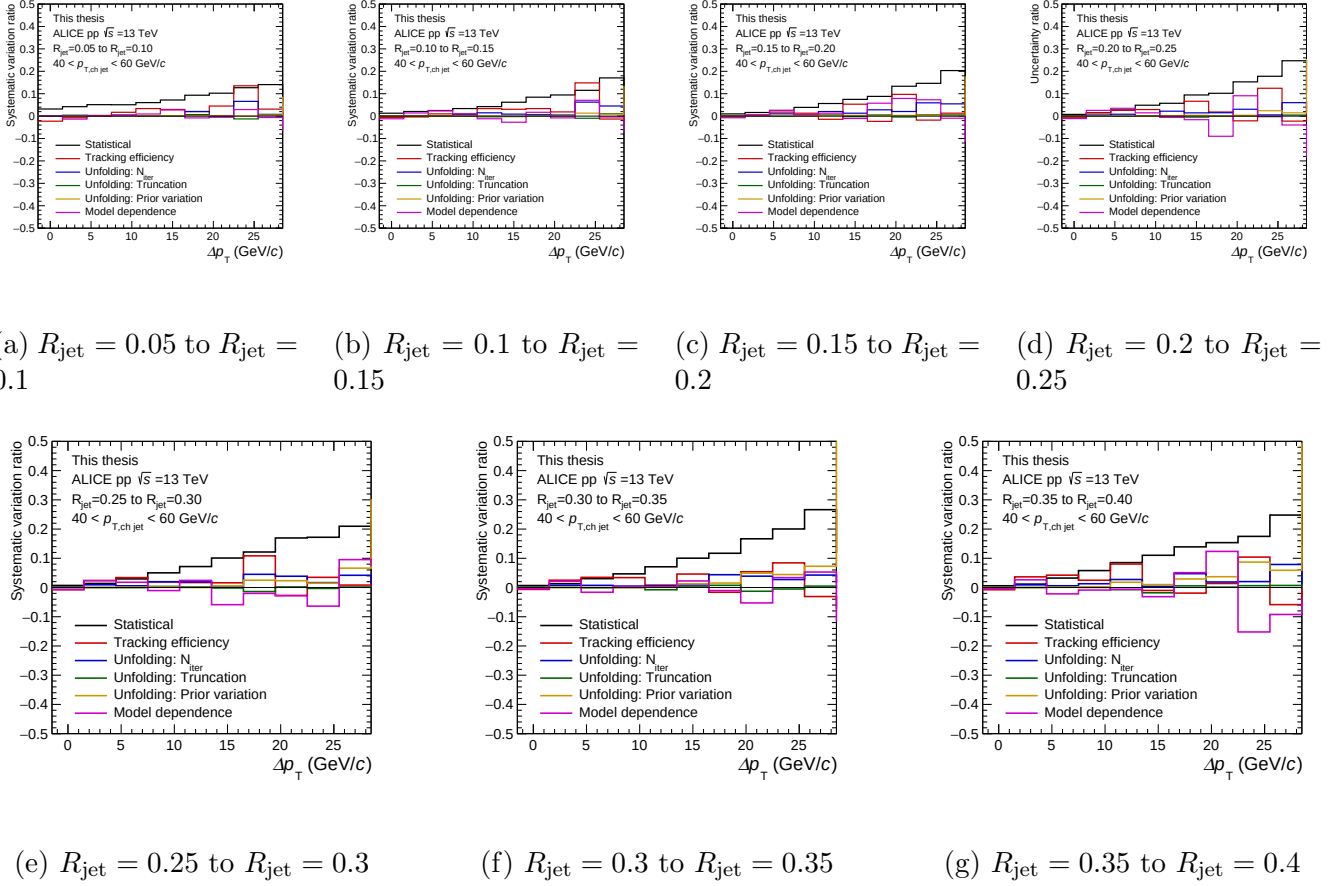


Figure 91: Overview of the relative systematic uncertainties for jet pairs with radius between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$. A selection to the jet p_T , $40 \leq p_T < 60$ GeV/c, of the narrow jet has been applied. The statistical uncertainty of the default unfolded distribution is also plotted as a reference.

fluctuations were shown in Sec. 12.2. This sections serves as a supplement providing the respective model comparisons for the remaining jet radii in Fig. 92. Additionally, the comparisons with the two generators of both the Δp_T distributions and the jet radius dependence of energy flow for jets with $40 \leq p_T < 60$ GeV/c are shown in Fig. 93, 94 and 95.

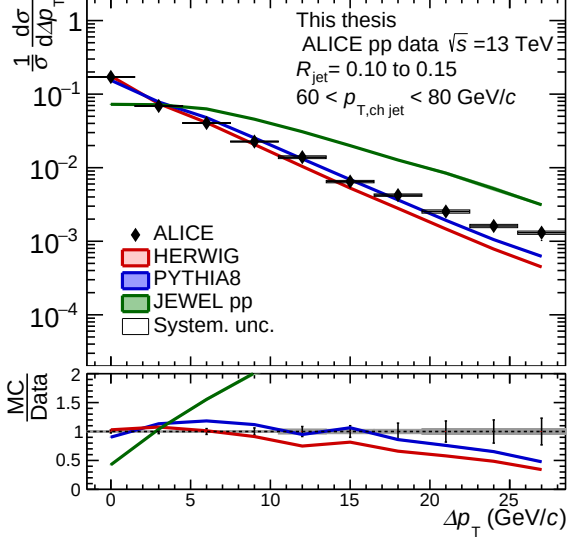
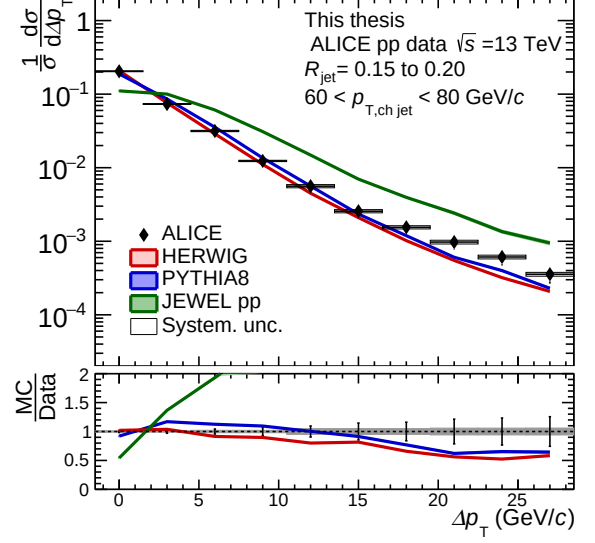
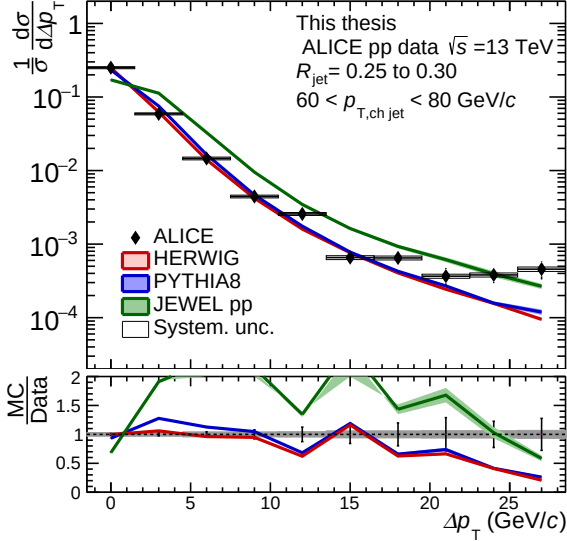
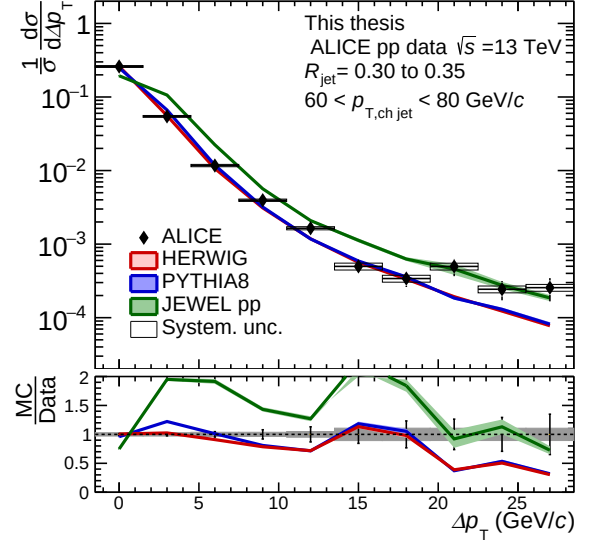
(a) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ (b) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.2$ (c) $R_{\text{jet}} = 0.25$ to $R_{\text{jet}} = 0.3$ (d) $R_{\text{jet}} = 0.3$ to $R_{\text{jet}} = 0.35$

Figure 92: Comparison of measured Δp_T distributions in ALICE pp data at $\sqrt{s} = 13$ TeV with model predictions for jets with radii between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

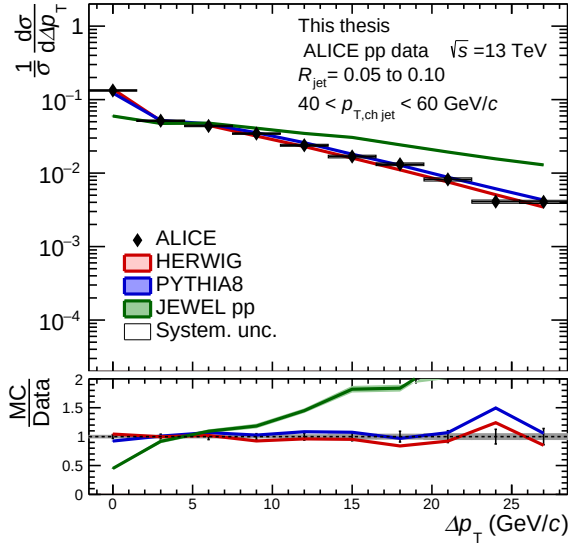
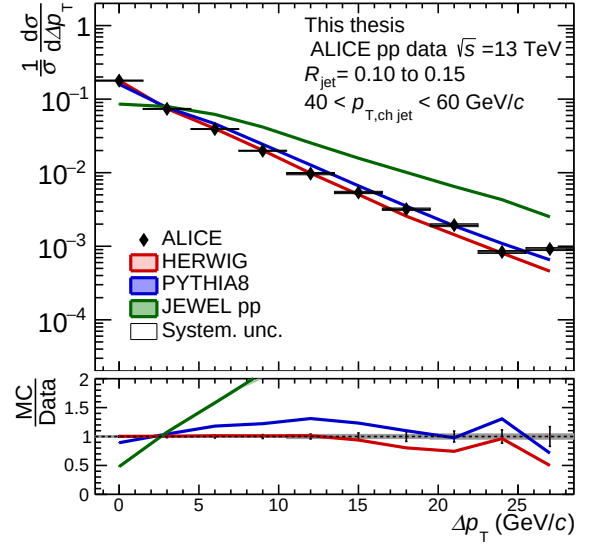
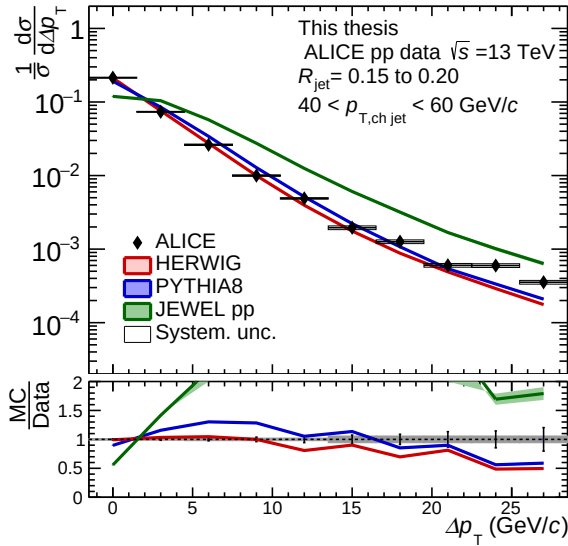
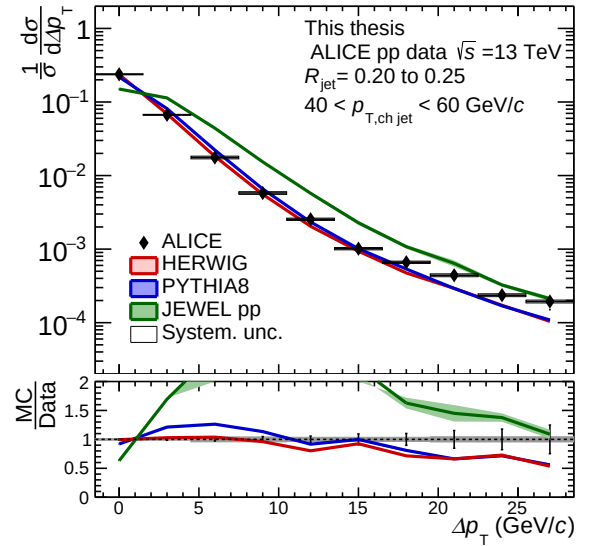

 (a) $R_{\text{jet}} = 0.05$ to $R_{\text{jet}} = 0.1$

 (b) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$

 (c) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.2$

 (d) $R_{\text{jet}} = 0.2$ to $R_{\text{jet}} = 0.25$

Figure 93: Comparison of measured Δp_T distributions in ALICE pp data at $\sqrt{s} = 13$ TeV with model predictions for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.25$. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c.

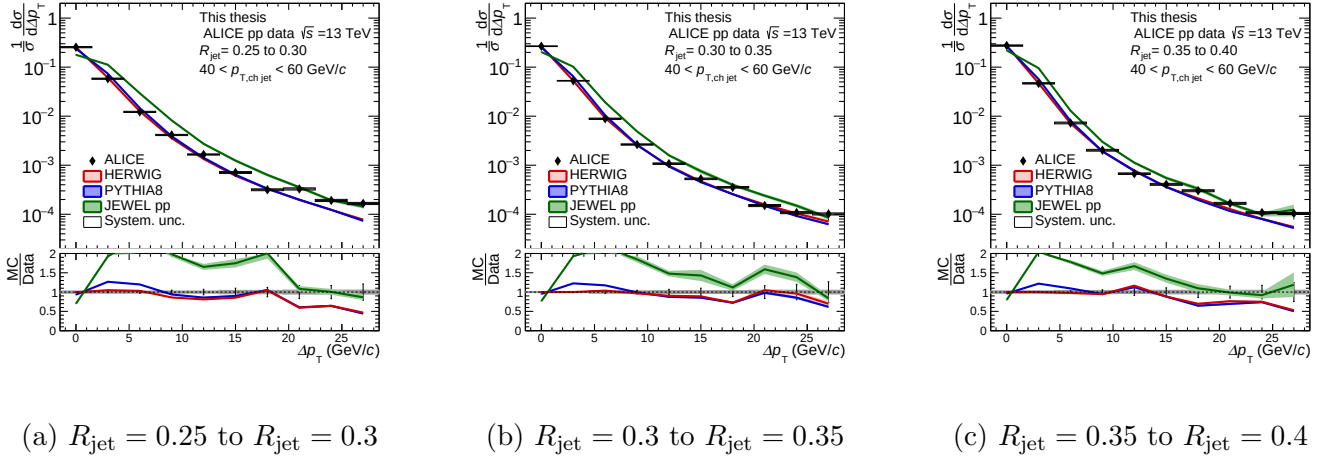


Figure 94: Comparison of measured Δp_T distributions in ALICE pp data at $\sqrt{s} = 13$ TeV with model predictions for jets with radii between $R_{\text{jet}} = 0.25$ and $R_{\text{jet}} = 0.4$. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c.

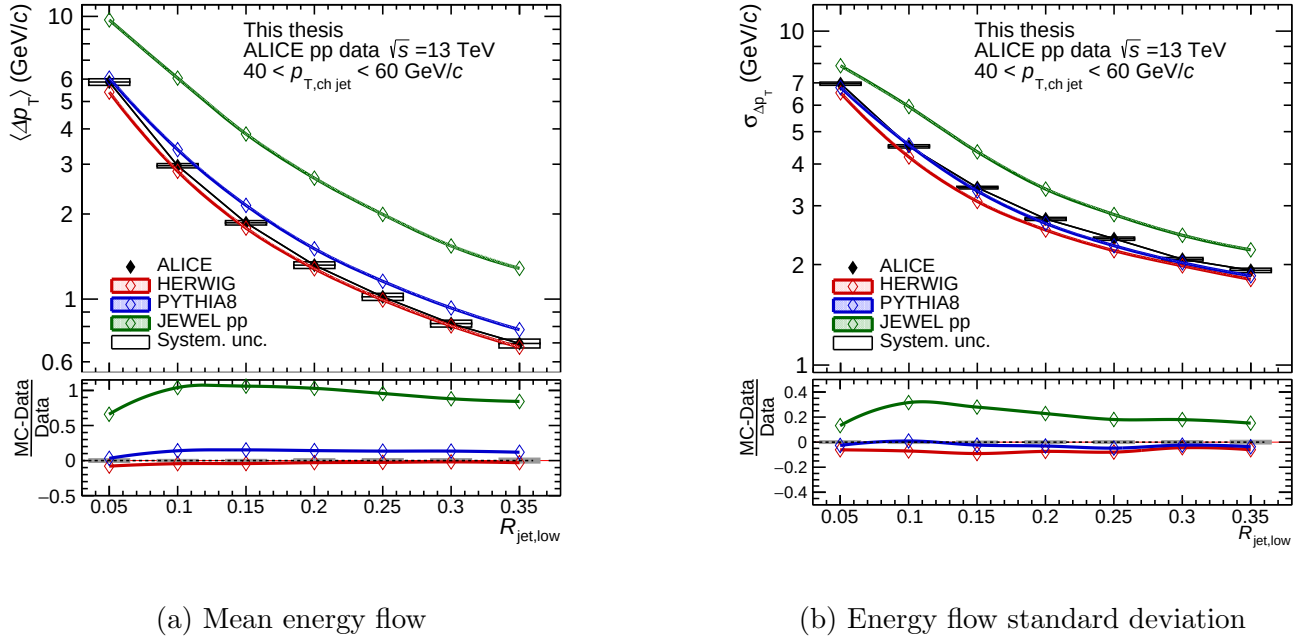


Figure 95: Comparison of mean energy flow (left) and its standard deviation (right) for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE pp data at $\sqrt{s} = 13$ TeV with model predictions. For each matched jet pair, the p_T of the narrow jet is between $40 \leq p_T < 60$ GeV/c.

B - Supplemental plots for the Pb-Pb measurement

This appendix section features additional plots of the energy flow measurement with the ALICE Pb-Pb data. Particularly, supplemental response matrix projections and closure test performances are presented in Sec. [B.1](#) and [B.2](#) respectively. Sec. [B.3](#) and Sec. [B.4](#) include their titular content for the jet radial pair which was not featured in the main text.

B.1 - Correction plots for ALICE Pb-Pb data

The projections of the response matrix with respect to the jet momentum for jet radii which were not shown in Fig. [57](#) of the main text are shown in Fig. [96](#). In addition the supplemental plots to Fig. [58](#) are presented in Fig. [97](#) for the rest of the jet radial pairs. These plots show that the correspondence between the generator and the reconstructed level information becomes less clear for jets with radius $R_{\text{jet} \geq 0.25}$. This effect along with the divergence of the closure tests for those jet radii motivated the restriction of the jet energy flow measurement to small jet radii.

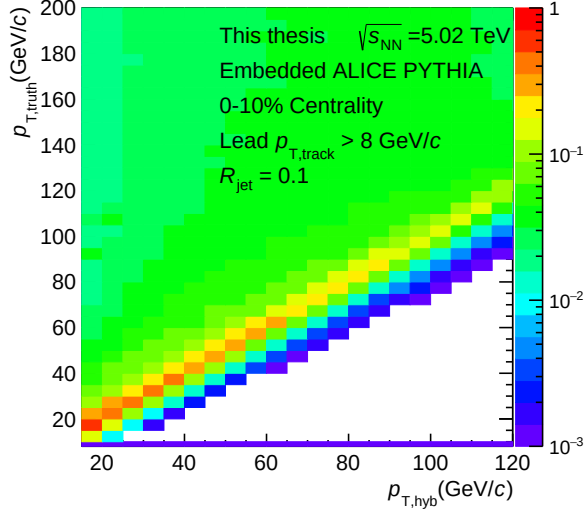
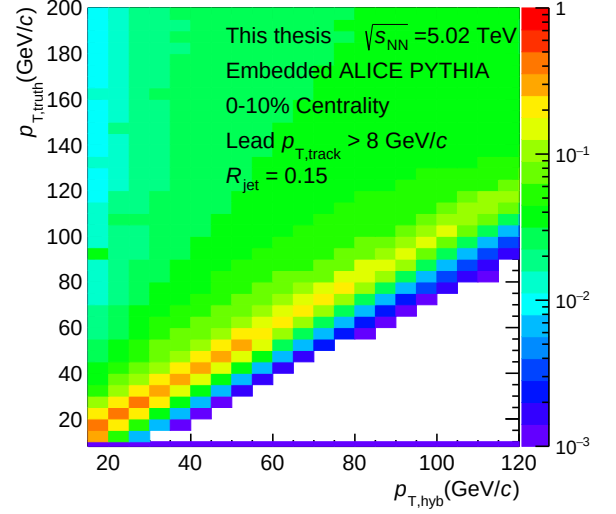
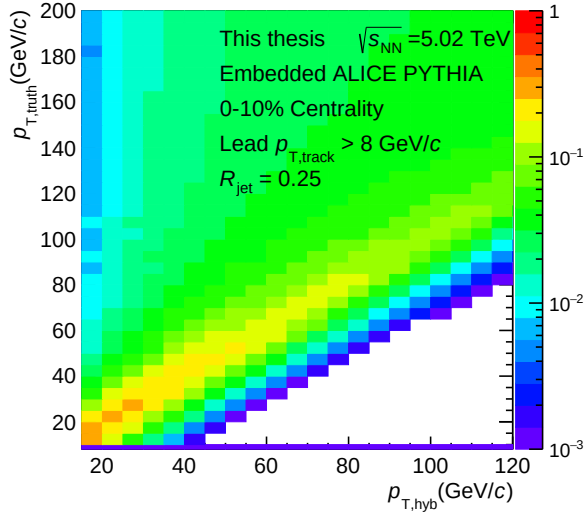
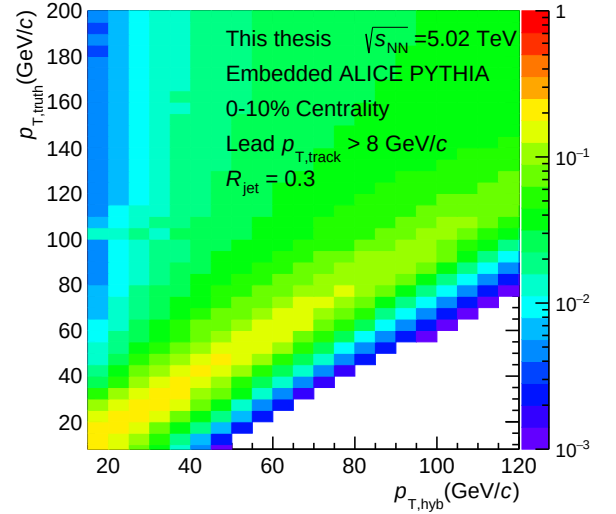
(a) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ (b) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.2$ (c) $R_{\text{jet}} = 0.25$ to $R_{\text{jet}} = 0.3$ (d) $R_{\text{jet}} = 0.3$ to $R_{\text{jet}} = 0.35$

Figure 96: Projections of the response matrix for p_T between truth and reconstructed level in ALICE embedded PYTHIA simulations for matched jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$.

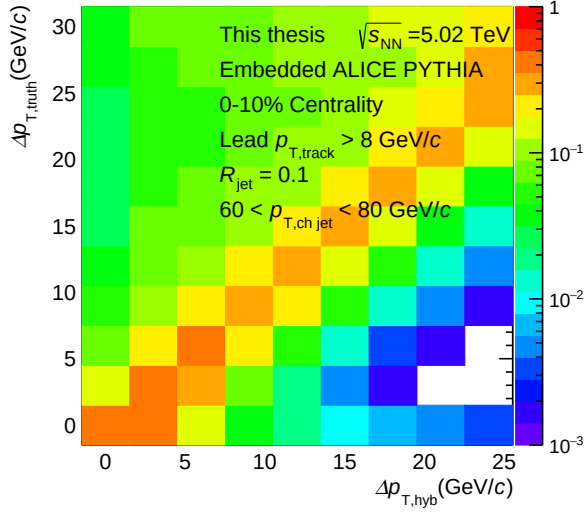
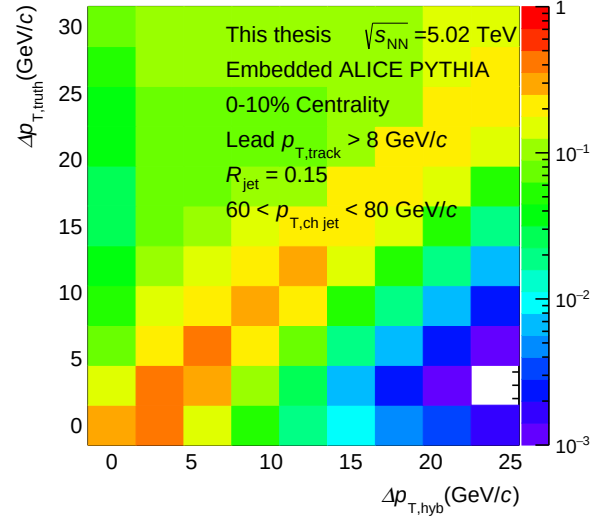
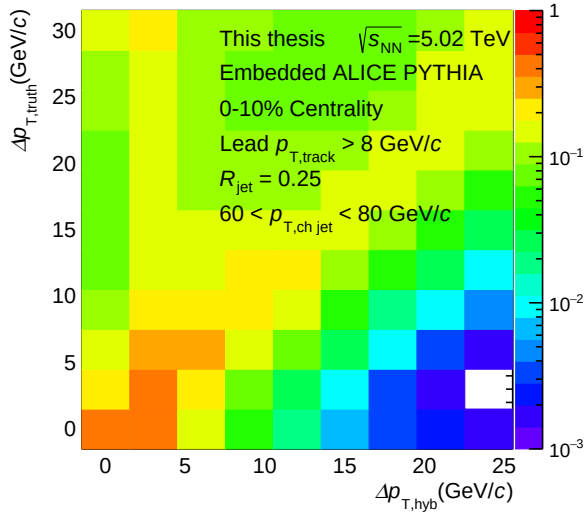
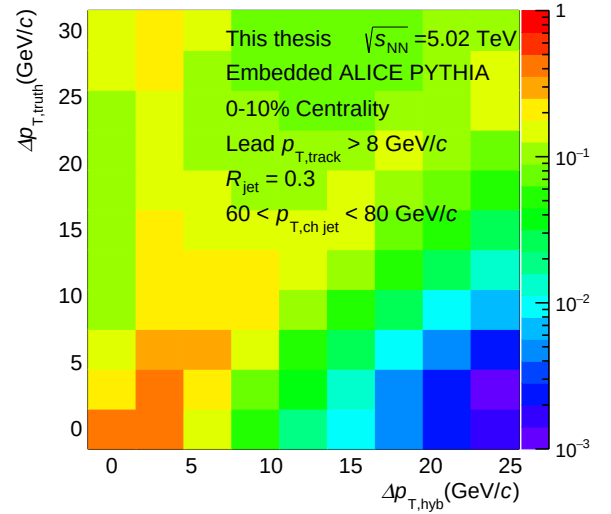

 (a) $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$

 (b) $R_{\text{jet}} = 0.15$ to $R_{\text{jet}} = 0.2$

 (c) $R_{\text{jet}} = 0.25$ to $R_{\text{jet}} = 0.3$

 (d) $R_{\text{jet}} = 0.3$ to $R_{\text{jet}} = 0.35$

Figure 97: Projections of the response matrix for Δp_T between truth and reconstructed level in ALICE embedded PYTHIA simulations for matched jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$. In all three panels a selection on the narrow jet's p_T at truth level, $60 \leq p_T < 80$ GeV/c, is applied.

B.2 - Closure tests for ALICE Embedded PYTHIA

The closure tests in both reconstructed (Fig. 99) and the generator (Fig. 98) level for the ALICE PYTHIA simulations embedded in Pb-Pb data are shown in this section. Specifically, this section shows the performance of closure tests for the jet radial pairs which were not shown in the main text.

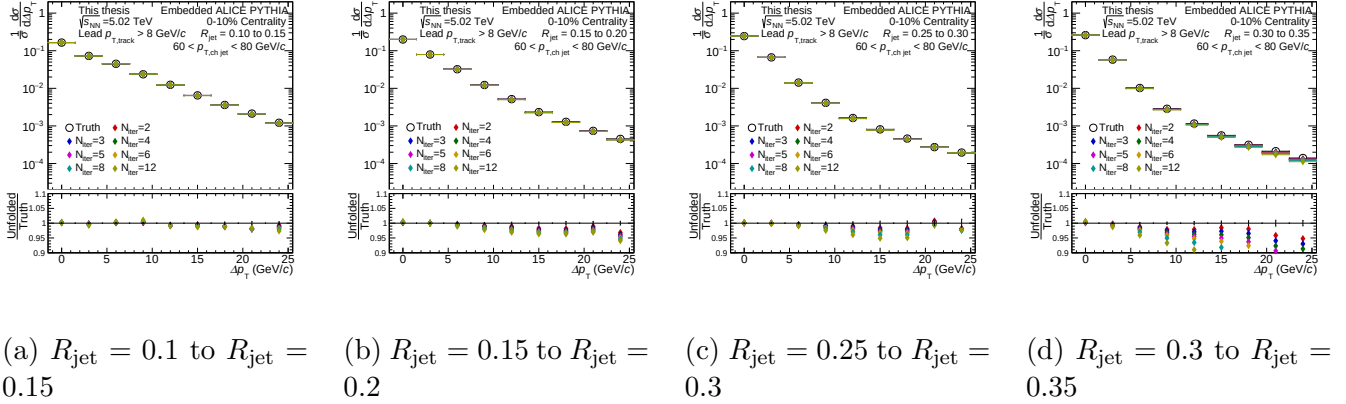


Figure 98: Performance of closure tests at the truth level for Δp_T distributions for jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$ in ALICE embedded PYTHIA simulations. The bottom panels show the ratio between the unfolded and truth level distributions. In all four panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

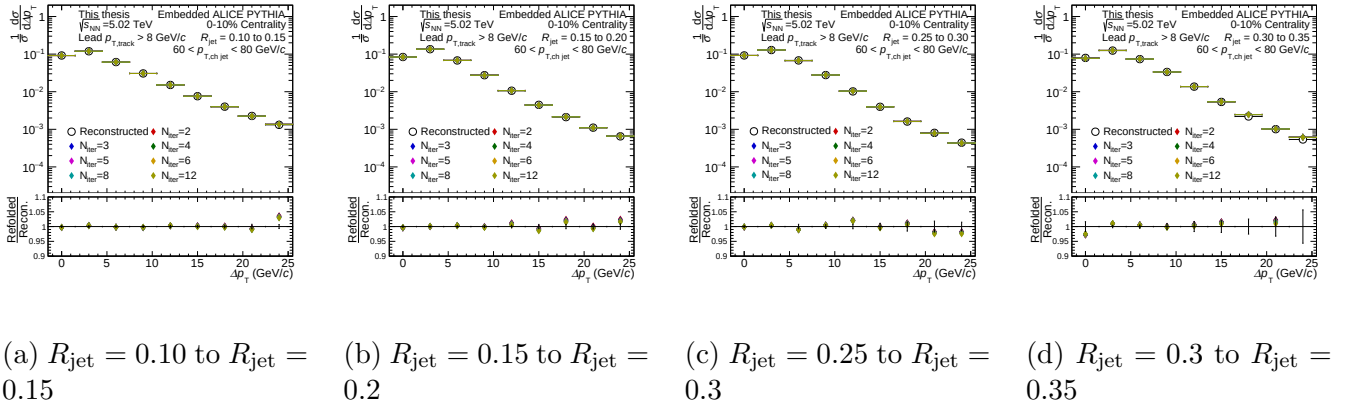


Figure 99: Performance of closure tests at the reconstructed level for Δp_T distributions for jet pairs with radius between $R_{\text{jet}} = 0.1$ and $R_{\text{jet}} = 0.35$ in ALICE embedded PYTHIA simulations. The bottom panels show the ratio between the refolded and detector level distributions. In all four panels, a jet p_T selection on the narrow jet, $60 \leq p_T < 80$ GeV/c, is applied.

B.3 - Systematic uncertainties for ALICE Pb-Pb measurement

The calculated systematic uncertainties of the energy flow measurement with the ALICE Pb-Pb data for the jet radial pair of $R_{\text{jet}} = 0.1$ to $R_{\text{jet}} = 0.15$ are shown in Fig. 100 of this section.

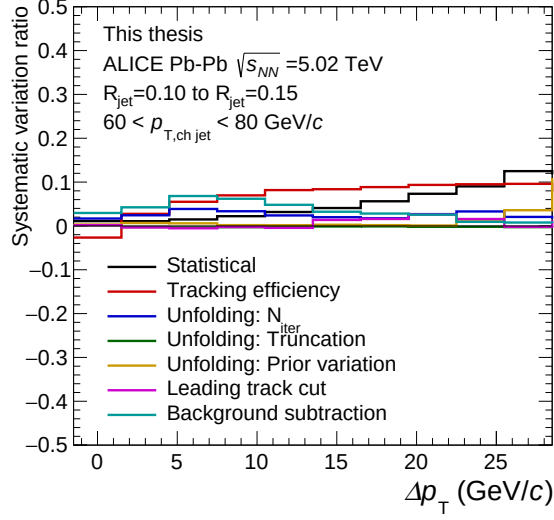


Figure 100: Overview of the relative systematic uncertainties for the smallest radial pair $R_{jet} = 0.1$ to $R_{jet} = 0.15$. A selection to the jet p_T , $60 \leq p_T < 80$ GeV/c, of the smaller jet radius has been applied. The statistical uncertainty of the default unfolded distribution is also plotted as a reference.

B.4 - Model comparison for ALICE Pb-Pb measurement

The comparison of the ALICE Pb-Pb energy flow measurement for the radial pair of $R_{jet} = 0.1$ to $R_{jet} = 0.15$ with the JEWEL model predictions are shown in Fig. 101.

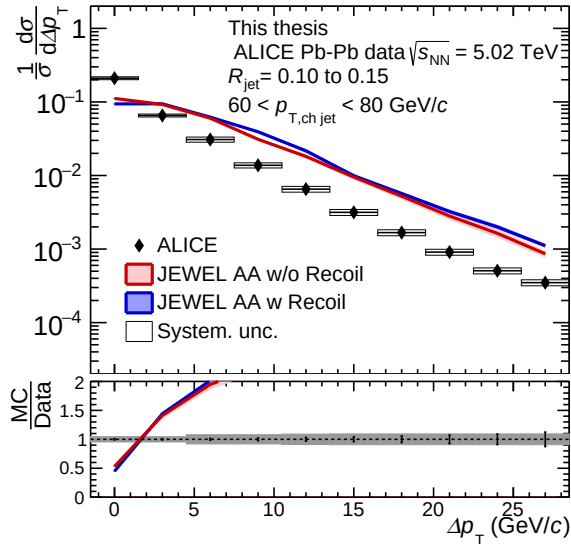


Figure 101: Comparison of measured Δp_T distributions in ALICE Pb-Pb data at $\sqrt{s_{NN}} = 5.02$ TeV with the JEWEL model predictions for radial jet pair of $R_{jet} = 0.1$ to $R_{jet} = 0.15$. For each matched jet pair, the p_T of the narrow jet is between $60 \leq p_T < 80$ GeV/c.

C - Additional discussion plots

This appendix section features plots referring the comparison of distribution for different collision systems. Sec. C.1 shows the comparison of Δp_T distributions for the different JEWEL operating modes in vacuum and within an external medium. Lastly, Sec. C.2 includes additional plots referring the dependence of the energy flow results on the collision energy.

C.1 - JEWEL Collision system comparison plots

The Δp_T distributions for the JEWEL simulations in pp and AA collisions, similar to the plots shown in Sec. 9.4, are displayed in this section addressing the jet radial pairs which were not covered in the main text.

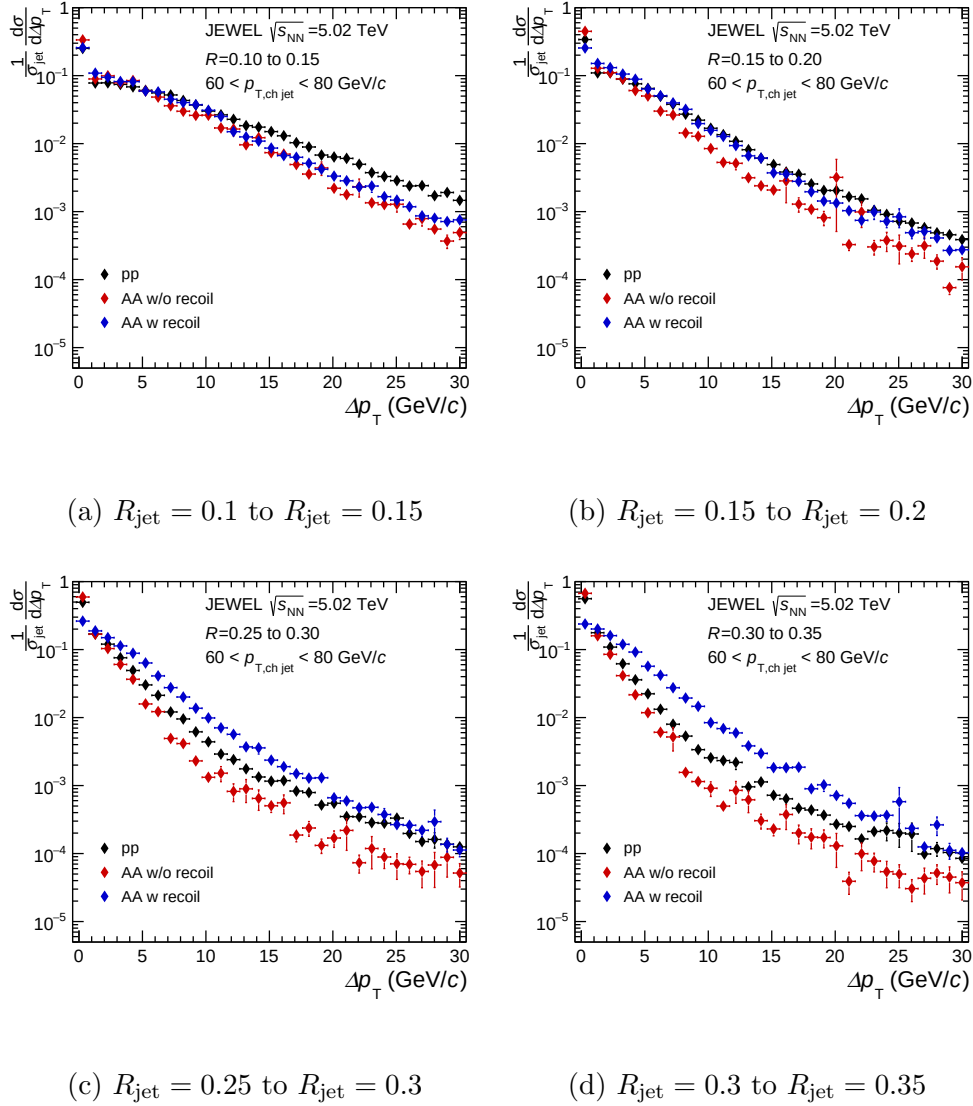
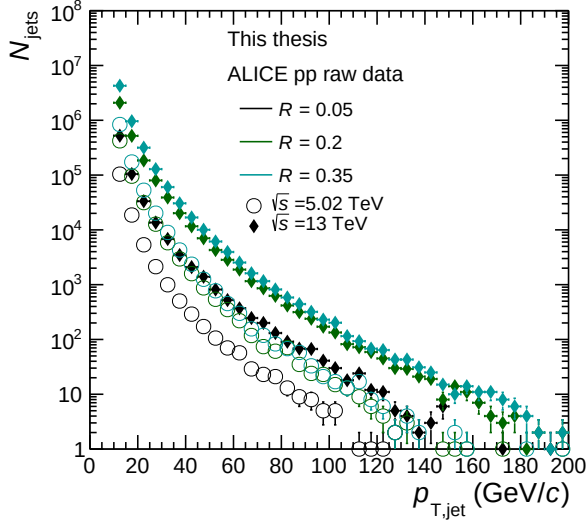


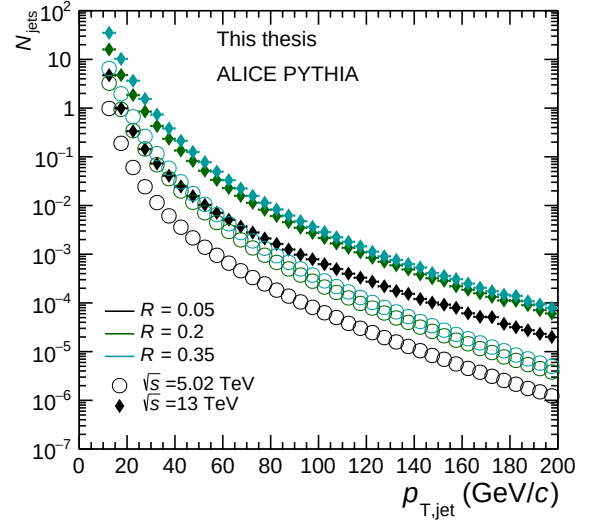
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C.2 - Collision energy comparison plots

The energy flow measurements with the ALICE data were made in different collision energies for pp and Pb-Pb case. The impact of this difference is very mild as it was discussed in Sec. 13.3. This section shows the jet p_T spectra (Fig. 103) in both ALICE data and PYTHIA simulations for the different collision energies to demonstrate the smoothness of the dependence.



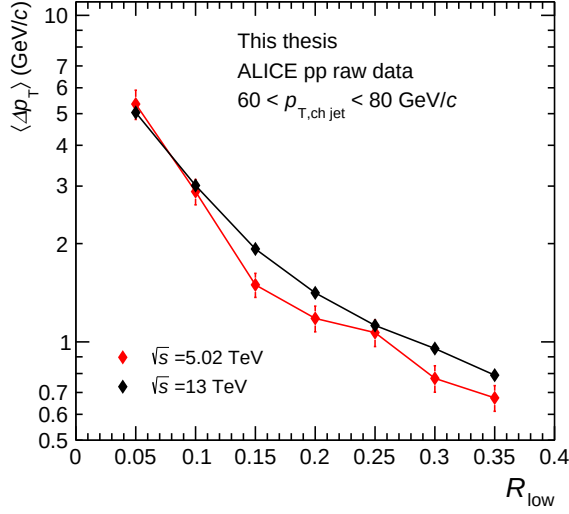
(a) ALICE pp raw data



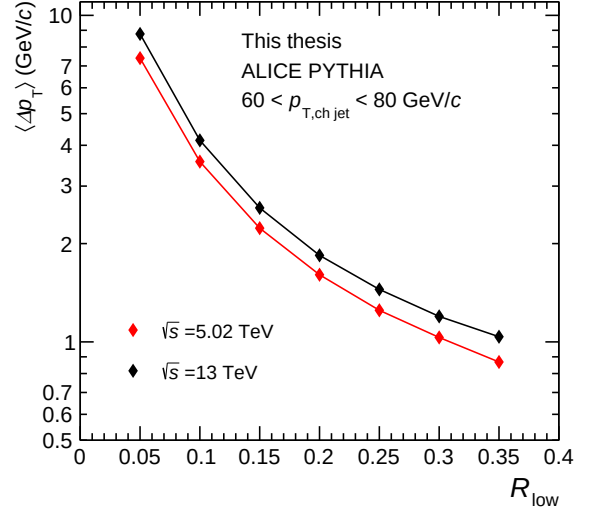
(b) PYTHIA simulations

Figure 103: Comparison of p_T spectra for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE pp data (left) and PYTHIA simulations (right) for different collision energies.

Lastly, the mean energy flow (Fig. 104) and the standard deviation of the Δp_T distributions (Fig. 105) as a function of the jet radius for the two collision energies are compared in ALICE data and PYTHIA simulations.

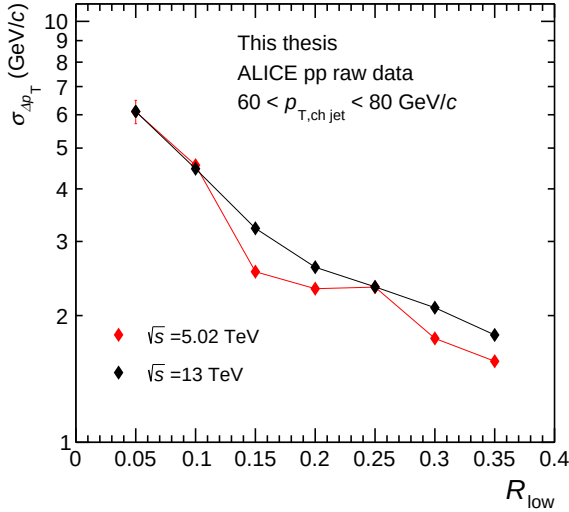


(a) ALICE pp raw data

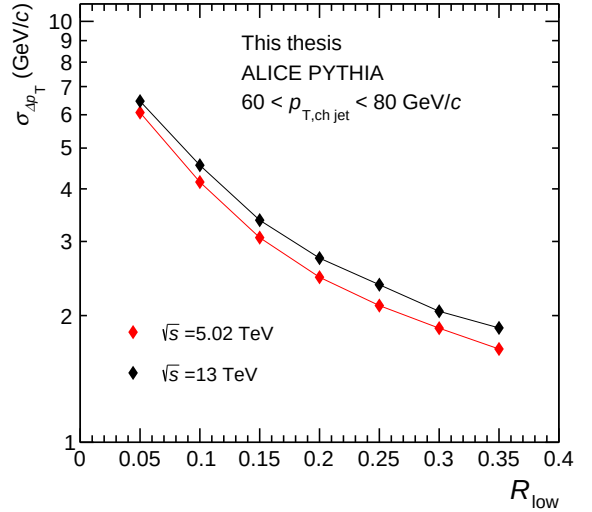


(b) PYTHIA simulations

Figure 104: Comparison of mean energy flow as a function of jet radius for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE pp data (left) and PYTHIA simulations (right) for different collision energies.



(a) ALICE pp raw data



(b) PYTHIA simulations

Figure 105: Comparison of energy flow standard deviation as a function of jet radius for jets with radii between $R_{\text{jet}} = 0.05$ and $R_{\text{jet}} = 0.4$ in ALICE pp data (left) and PYTHIA simulations (right) for different collision energies.

Acknowledgements

This PhD thesis represents the culmination of several years of effort, learning, and collaboration. Along the way, I have had the privilege of working with and learning from many brilliant individuals whose guidance has been instrumental to my academic growth and the success of this project. I am truly grateful for their contributions.

First and foremost, I would like to thank my promotor, Thomas Peitzmann, for his invaluable supervision throughout this journey. Thomas, your enthusiasm during our discussions about the physics interpretations of my research findings was essential in maintaining clarity and focus on the project's objectives. I am also particularly appreciative of my supervisors, Marta Verweij and Marco van Leeuwen, for their unwavering support. Marta, your patience in addressing technical analysis details and your understanding of the challenges faced by junior researchers have been immensely beneficial. Marco, you were not just a supervisor but also a mentor who introduced me to the fascinating world of heavy-ion physics and jet studies. I have gained invaluable insights from you, both as a physicist and a researcher. I deeply value our engaging scientific discussions, your pragmatic approach to problem-solving, and your readiness to assist with the minor software challenges that often hindered the research process.

I would also like to express my heartfelt appreciation to my senior colleagues, Panos Christakoglou and Alessandro Grelli, for their generous support and willingness to share their knowledge and ALICE experience. Alessandro, our conversations over coffee —ranging from physics to broader, sometimes controversial, topics— were always intriguing and brought plenty of laughter. Panos, your guidance through the challenges of PhD life, along with your professional (and occasionally cynical) advice, has been invaluable. I am especially grateful for your efforts in nurturing a collaborative and supportive team spirit within GRASP.

This acknowledgment section would not be complete without recognizing the positive influence my peers and colleagues have had throughout this endeavour. A special thanks goes to Gijs van Weelden, not only for our long, helpful physics (and software) discussions but also for the mutual support we shared during challenging times and for enduring those seemingly endless days at Nikhef together. I'm also thankful to Bas Hofman for his constant positivity, eagerness to assist, and his crucial contributions to the HERWIG and PYTHIA fast simulations. A heartfelt thanks to Shi Qiu, my office mate and conference travel buddy, for the camaraderie and support —especially during our quarantine adventure in Switzerland. I'd also like to express my gratitude to Ivan Ravasenga for his assistance with the ALICE service task, his friendship and hospitality during the ITS2 commissioning shifts. I'm thankful to my fellow junior colleagues, Rik Spijkers, Johanna Lömker, Olaf Massen, Noor Koster, and Justus Rudolph for their contagious enthusiasm and the engaging chats that brightened coffee breaks, lunches, and Tuesday borrels. A special mention goes to Melissa Lopez for sparking my interest in machine learning and for our enjoyable conversations about politics and the commonalities in Mediterranean cultures. To my fellow DUWO-neighbors, Enzo Tapia and Anna Puecher, our (tentatively-allowed) backyard BBQ sessions are certainly fond memories.

Beyond the professional sphere, I owe my deepest thanks to my closest friends, Emmanuel and Filippas. Manny, sharing the highs and lows of our PhD experiences has undeniably strengthened our bond. I'm immensely grateful for the countless hours spent in long-distance calls, our adventures abroad, and the much-needed escapes through our RPG sessions. Filip, although life has taken us on different paths, I truly appreciate your continuous support. Whether hanging out in person or catching up online, our conversations, often punctuated with fond memories of our college days, have provided great comfort. To my beloved Christina, your endless patience, encouragement, and optimism have been my

guiding light through the PhD experience. Your unwavering confidence in me, even during the most difficult moments, has kept me grounded and given me the strength to push forward.

Finally, I owe an immense debt of gratitude to my parents, Evan and Sofia. Your boundless love, faith, and encouragement have been the foundation of my success. In moments of uncertainty, it was your reassurance that motivated me to persevere, and I truly wouldn't be where I am today without you. I also want to extend my heartfelt appreciation to my brother Asteris and his partner Stella. Your steadfast support and the unique perspectives you both offer on the academic and industrial realms have been both enlightening and inspiring.

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